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White Sands Missile Range 2007 Urban Study: Data Processing – Volume DP-1 (Sonic Calibration)

by Gail Vaucher, Robert Brice, Sean D'Arcy, Manuel Bustillos, and Ron Cionco

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14. ABSTRACT

Calibrating sensors is an important step in determining the confidence one has in the quality of data acquired. Without access to a National Institute of Standards and Technology (NIST) wind tunnel facility, side-by-side relative calibration (against a NIST calibrated sensor) is an alternate method for calibrating meteorological sensors. For the *White Sands Missile Range 2007 Urban Study* (*W07US*), a Pre- and Post-*W07US* calibration was conducted on the 27 ultrasonic anemometers (sonics) slated for the *W07US* project. This technical report documents the *W07US* relative calibration design, calibration data processing method, implementation, results, and some of the lessons learned from the Pre- and Post-*W07US* calibration project.

15. SUBJECT TERMS

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Summary

Calibrating sensors is an important step in determining the confidence one has in the quality of data acquired. Without access to a National Institute of Standards and Technology (NIST) wind tunnel facility, side-by-side relative calibration (against a NIST calibrated sensor) is an alternate method for calibrating meteorological sensors. For the *White Sands Missile Range (WSMR) 2007 Urban Study (W07US)*, a Pre- and Post-*W07US* calibration was conducted on the 27 ultrasonic anemometers (sonics) slated for the *W07US* project. These sonics were organized in groups of 10 and mounted in a lateral array between 2 parallel buildings. A sonic previously calibrated against a NIST standard was selected as the "standard" and placed in the middle of the arrays. The six sonics most recently calibrated against a NIST standard were placed in the end positions of the lateral array, as these locations were most vulnerable to building airflow effects.

Prior to the analysis, the calibration data was examined for error flags, missing data, duplicate time stamps, and time synchronization. An independent verification of the time averaging equation, and the relative calibration equation, was conducted to ensure the accuracy of the calibration tools and procedures.

The data analysis examined various averaging lengths for calculating the relative calibration. The two that were included in the interpretation of results were the 1-min averages, which produced the largest population, and the 15-min averages, which displayed the narrowest standard deviation.

Building effects were identified as the main hazard for this type of side-by-side calibration design. To assess the building influence on the analysis, the population sample was examined. Reviewing the spatial distribution of data, some tapering off of resources were observed as the sensor placement neared the north and south buildings. However, these smaller resources still exceeded 1200 data points and, therefore, the building effect was not identified as a major concern at this point in the analysis.

The relative calibration results were analyzed by examining each of the Pre- and Post-Calibration groups separately, as a function of the u-, v-, and w-wind components. The northern two positions in the lateral array were flagged as incongruous with the other results. The v-component in the Post-Calibration dataset was also flagged as having three data points inconsistent with the other findings. The possible cause for these patterns was discussed and some lessons learned suggestions were made. Extracting these patterns, the remaining calibration differences were within ±0.5 m/s and the Pre-Calibration groups fell within ±0.3 m/s. Each delta (Δ) component held a unique general pattern: Δu showed an underestimation of the standard that gradually decreased from positions 3 to 4 and increased from positions 6 through 10. Δv showed a negative slope line from positions 3 (and sometimes position 1) through 10.

What started as an overestimation of the standard on the north side of the array ended up as an underestimation on the south side. The Δw trend showed a positive slope. The underestimation of the standard on the north side shifts to an overestimation on the south side. While some of these trends may be linked to the building's influence, the data hovers around the ideal result of zero. This near zero observation was the anticipated outcome of the calibration effort.

There were several lessons learned, which we summarize here:

1. To avoid the building's influence, sensors should be mounted no closer to the north building than position 3 (about 7.5 m from the wall) and no closer to the south building than position 10 (about 9.0 m from the wall). The conservative recommendation was to place the southernmost sonic in position 9.

2. The calibration results may be more closely aligned to a wind tunnel if the thresholds for acceptable sensor differences were increased from 1 m/s to 5 m/s, or even 12 m/s. Note: The natural environment may not present such consistently high velocities.

3. The NIST standard sonics were mounted at the lateral array end points. This choice helped anchor the interpretation of the calibration data analysis.

4. Position 5 in the 10-position lateral array was the best location between the test site buildings for the standard sonic. This position remained consistent for all Pre- and Post-*W07US* calibration group data acquisition periods.

5. The sensor mounting specifications (sensor height above ground and distance between sensors) showed no hint of interference for the westerly and easterly airflows. Therefore, these specifications are recommended for future relative calibration efforts.

In conclusion, we have observed that the component data acquired by these sensors were within 0.5 m/s of the standard sensor, with some additional sensors being much more closely aligned with the standard. This result may not be as tightly aligned as the controlled environment of a NIST wind tunnel calibration; however, for using only the natural airflow as the medium for the side-by-side comparisons, these results were considered acceptable.

1. Introduction

Atmospheric urban field measurements are the foundation for extracting repeatable, and therefore, predictable urban atmospheric patterns. These patterns are parameterized into mathematical algorithms. The algorithms are integrated into Army models, which then contribute to Army decision aids and become tools for improving military efficiency and effectiveness in the urban environment (Vaucher et al., 2007). Before these tools are used, one needs to ask, “How good are these tools, models, algorithms, and measurements?” The answer is rooted in an even more fundamental question, “How well did the sensors take the atmospheric measurements?” This latter question is the primary topic of this technical report.

1.1 *WSMR 2007 Urban Study* (*W07US*)

In March 2007, the U.S. Army Research Laboratory (ARL) conducted a field study, *W07US*. The mission objectives for this study consisted of characterizing the urban atmosphere around and above a single building, as well as other technological and research application goals (see ARL-TR-4255 (Vaucher et al., 2007)). The characterization effort was divided into two parts: the dynamic (airflow) and the thermodynamic (atmospheric stability) contributions. Seven towers and five tripods supported 51 sensors that were strategically placed to capture these two targeted elements. One of the primary sensors quantifying the dynamic character was the Ultrasonic Anemometer (Sonic), RM Young Model 81000 (figure 1). The total number of sonics required for *W07US* was 27: 25 fielded units, 1 backup unit, and 1 unit designated as the relative calibration standard. Before any sensor was accepted as a field study instrument, it was subjected to, and required to pass, a Pre-*W07US* calibration test. Following the field study execution, each sensor used was again subjected to a calibration test. In section 1.2, sensor calibration will be explained.

Figure 1. The RM Young 81000 Ultrasonic Anemometer was the primary sensor quantifying the dynamic character of the *W07US* urban site.

1.2 Sensor Calibration

Quantifying the atmosphere is done by sampling various atmospheric elements with scaled tools, or sensors. The quantified values or data are then integrated into a variety of applications. The value of the applications is often a direct function of the data input, and for this reason, standards for the atmospheric sampling were developed. Describing how the sampled data compare to these standards is the primary goal of the sensor calibration data processing and analysis.

In the United States, the American Society of Testing and Materials (ASTM) has established sensor performance specification standards. The actual standards are currently maintained by the National Institute of Standards and Technology (NIST). From these NIST standards, all other sensors are compared or calibrated. (Brock and Richardson, 2001)

Calibration can be conducted in several ways. The most direct method is to compare a given sensor output directly with that of a nationally recognized sensor output standard, such as those used at NIST. We call this method, "absolute calibration." When this method becomes impractical, perhaps due to logistics or economics, a sensor that has been calibrated at NIST is then brought to other sensors not calibrated at NIST. This second-level standard now becomes

the benchmark for determining acceptable measurements for all other sensors. This latter method is called “relative calibration.” It could be argued that both methods are “relative.” However, the unchanging nature of the standard NIST sensor and testing environment is what elevates the sensor comparison terminology to a distinguished “absolute calibration.”

1.3 Basic Measurement Terminology

There are several important terms used when evaluating measurements. The first term is “accuracy.” Accuracy is “the relation between the measured and ‘true’ value, or the closeness to an accepted standard such as those maintained by the National Bureau of Standards” (Fritschen and Gay, 1979).

Note: On 1901 March 3, the U.S. Congress established the National Bureau of Standards (NBS) as part of the Department of Commerce. In 1988, the NBS was renamed NIST (Infoplease, 2008).

Accuracy is often referenced in terms of “inaccuracy.” For example, if the sonic specifications state that wind direction (WD) is accurate to ±2° over a given range of 0 to 30 m/s, then a WD of 180° sampled at velocities between 0 and 30 m/s can be interpreted as follows: there is a “95% probability that the actual wind direction is 180° ±2°, if the errors were randomly distributed in a Gaussian distribution” and there are no other known systematic or random sensor errors. (Brock and Richardson, 2001)

Mathematically, accuracy can be represented as the following:

$$\text{Sensor value} = \text{“true value”} + \text{error} \tag{1}$$

Where error = inaccuracy, then:

$$\text{Inaccuracy} = \text{sensor value} - \text{“true value”} \tag{2}$$

A second term, often confused with accuracy, is “precision.” Precision refers to “the variability observed among numerous measurements of a quantity” (Fritschen and Gay, 1979). This means that if a sensor was dropped, the sensor may still consistently report the same value when subjected to the same conditions. However, the value being reported may no longer be aligned with the standard/“truth.” That is, the sensor’s accuracy will have changed but the precision is still valid.

Finally, factory-set “thresholds” refer to a sensor’s sensitivity limit and resolution. For the sonic, this is determined by acoustic path length and time measurement resolution limits in the sensor circuit (Poinsett, 2008).

1.4 Basic Sonic Sensor Terminology

The ultrasonic anemometer (sonic) measures three-dimensional wind velocities (u,v,w) and speed of sound based on the transit time of ultrasonic acoustic signals. The u-, v-, and w-component wind velocities are sensor outputs. Typically, these are oriented with the u-axis aligned east-west, the v-axis aligned north-south, and the w-axis aligned in the vertical. The manufacturer's default for the ultrasonic model 81000 set the +u values as wind from the east, the +v values as wind from the north, and the +w as wind from below (RM Young Manual). Unfortunately, the academic meteorological community interprets the u and v wind vectors in the exact opposite directions; therefore, all u and v data values were reversed prior to any analysis.

In summary, for this calibration data processing, all sonic data values for the u-, v-, and w-components had (and have) the following orientations:

- +u = wind vector representing winds from the west going to the east
- +v = wind vector representing winds from the south going to the north
- +w = wind vector representing winds from below going upward; up drafts

Likewise, the negative vectors are as follows:

- -u = wind vector representing winds from the east going to the west
- -v = wind vector representing winds from the north going to the south
- -w = wind vector representing winds from above going downward; down drafts

1.5 Additional Reference Material on the *WSMR Urban Studies*

The *WSMR Urban Study* documentation has been evolving as the original researchers complete their investigations. The current reference materials available to the reader include the following:

1. ARL-TR-4255 (Vol.1): An overview of *W07US* design, preparations, and field study execution.
2. ARL-TR-4439 (Vol. DP-1): Data Processing – Pre- and Post-*W07US* sonic calibration (this report).
3. ARL-TR-4441 (Vol. DP-3): Data Processing – airflow qualitative assessment.
4. ARL-TR-4256 (Vol. AS-1): A comparison of stability results from *WSMR 2003 Urban Study* (*W03US*) and *WSMR 2005 Urban Study* (*W05US*).
5. ARL-TR-4452 (Vol. AS-2): Data Processing – stability qualitative assessment, and inter-*Studies* comparison.

2. *W07US* Data Processing

Data processing begins at the inception of a field study, continues throughout the field study execution, and well into the Post-*Study* activities. Ultimately, the data processing effort culminates in a quality dataset and a valuable set of lessons learned for the subsequent scientific field studies.

In this section, a description of the *W07US* data and data processing plan set the stage for an explanation of the *W07US* calibration data processing method. The implementation of the method, and the subsequent findings, will then address the original question, "How well did the sensors take the atmospheric measurements?"

2.1 *W07US* Data and Data Processing Plan

The large, complex *W07US* dataset was the product of a four-phased field study. As per the field study's Test Plan, these phases included the following:

- 2006 July–2007 Mar.: *W07US* Preparation
- 2007 Feb./Mar.: Pre-*W07US* Calibrations
- 2007 Mar./Apr.: *W07US* Field Portion
- 2007 Apr./May: Post-*W07US* Calibration and Preliminary Summary submission

During the *W07US* Preparation phase, testing was done on the hardware (towers, tripods, etc.), software (data acquisition systems (DAS), data monitoring, data presentation, etc.), and sensors. The Pre- and Post-*W07US* Calibration phases included side-by-side relative calibration of common sensors, and the running of "rpm" and WD tests on the wind monitors. The Field Portion was the actual execution of the field study. For an overview of the *W07US* Design, Preparation, and Field Portion execution, see ARL-TR-4255 (Vaucher et al., 2007).

The Pre- and Post-*W07US* calibration dataset represented about 38% of the total *W07US* data acquired and is the subject of this report. The field portion or "main dataset" represented approximately 62% of the total 52 GB dataset.

The *W07US* thermodynamic data resources evaluated included 26 sensors linked by 5 Campbell data logger systems. The thermodynamic variables stored included pressure, temperature, humidity, winds (1-min samples), and solar radiation. All thermodynamic data were saved as 1-min average samples.

The *W07US* dynamic data originated from 25 sonic sensors, sampling at 20 Hz. The dynamic data variables included component winds (u,v,w), temperature, speed of sound, and error flags. Due to the high frequency of acquisition, these raw dynamic data files were significantly more cumbersome than the rest of the dataset.

At the inception of the *W07US* project, the *W07US* Test Plan called for all 51 sensors to sample data 24 h per day, 7 days per week, over an uninterrupted 2-week period. To achieve this goal, the Test Plan required each sensor to be monitored daily. This monitoring consisted of downloading data from all sensors, calculating 1-min averages, plotting/printing each variable's time series, and reviewing the output for system, software, and/or sensor failures. The implementation of the Test Plan employed a monitoring group of four professionals, who, on average, reviewed over 388,000,000 datum points (approximately 1 day's worth of data) over a 4–5 h time period during each test day.

Once all the *W07US* data were acquired, a pre-planned, three-step Post-*W07US* Data Processing Plan was implemented. These steps consisted of (1) processing the *W07US* calibration data, (2) processing the main dataset with a focus on the overall quality of the acquired data, and (3) processing the main dataset with a focus on the data quality with respect to the intended scientific objectives. Due to time constraints, the three Post-*W07US* data processing steps were addressed concurrently, and the scope of the *W07US* calibration data processing step was reduced to concentrating on only the sonic data. In the next section, the method used for the *W07US* sonic calibration data processing is explained.

2.2 The *W07US* Calibration Data Processing Method

The *W07US* calibration data processing method consisted of six major milestones:

1. Acquire calibration data from lateral sonic arrays (to simulate a NIST wind tunnel).
2. Process the Pre-*W07US* sonic calibration (Pre-Calibration) data.
3. Process the Post-*W07US* sonic calibration (Post-Calibration) data.
4. Compare Pre-*W07US* and Post-*W07US* sonic calibration (Pre- and Post-Calibration) results.
5. Save sonic calibration adjusted dataset separate from original data.
6. Document results.

Each milestone will be described in the following subsections. The implementation of these milestones is discussed in section 3.

2.2.1 Lateral Sonic Array

The lateral sonic array was designed to simulate a NIST wind tunnel environment. The closest natural "wind tunnel" scenario available to *W07US* was a building canyon that ran from west to east along the south side of the subject building. The climatological-prevailing winds during the Pre- and Post-Calibration data acquisition periods were reported as westerly and southwesterly; therefore, this south canyon was selected as the sonic calibration site. Understanding that canyon flows come with built in hazards to the calibration mission, we accepted the potential cause for trouble in exchange for the lack of funding needed to run individual sonic wind tunnel calibrations.

The calibration test site design included five 2 m tripods placed side-by-side between the buildings. Each tripod supported 2 sonics, so that 10 sonics simultaneously sampled data at one time. The sonics that had been recently calibrated in a wind tunnel against a NIST standard were positioned at the two ends of the lineup, closest to the buildings (positions 1 and 10 in figure 2). These were the positions that were most vulnerable to flow distortion generated by the local forcing (building proximity). A NIST-calibrated sonic standard, common to all the side-by-side runs, was mounted nearest to the center, in position 5, for all sampling sessions. Position 1 was defined as the northern-most sonic position of the configuration. During the Pre-*W07US* Calibration, this sonic was 4.30 m from the building. During the Post-*W07US* Calibration, this sonic was 4.55 m from the building. Figure 2 shows a side view schematic of the calibration design, as well as an overview. The spacing shown in the schematic is idealistic. During the actual Pre- and Post-calibration data acquisition, there was a need for periodic access into the southern building, therefore, the distance between position 10 (southern most sonic) and the south building was 9 m during the Pre-*W07US* Calibration and about 9.2 m during the Post-*W07US* Calibration.

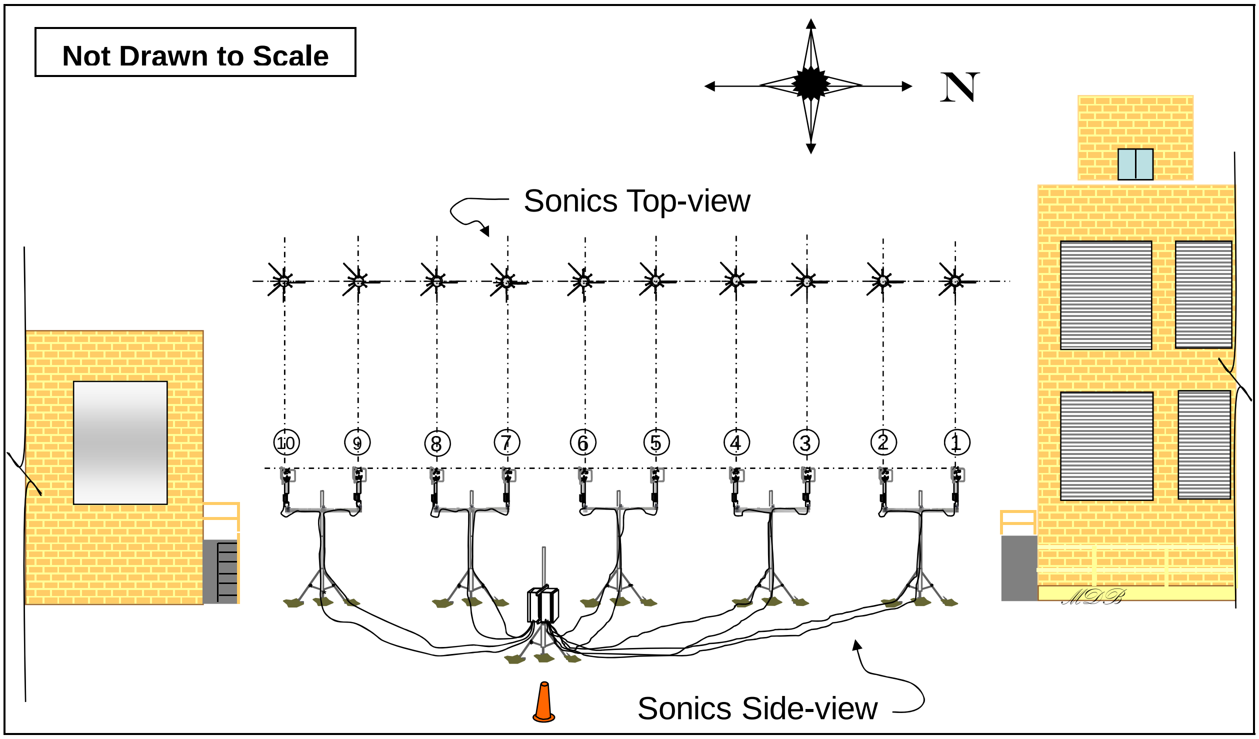


Figure 2. Schematic of the *W07US* calibration test site layout as seen from the side and top views.

Figure 3 is from an earlier study (*W05US*), in which the same side-by-side relative calibration was employed. This photo captures the horizontal alignment as seen through the 10 sonic sensors during a calibration period.

Figure 3. Photograph of the side-by-side sonic alignment during a relative calibration.

Note: The photo was taken during *W05US*.

The Pre-*W07US* and Post-*W07US* calibration session specifications for sensor heights and distances between sonics/the buildings were recorded and are included in appendix A. The targeted sensor height was 2.5 m above ground level (AGL). Since the relatively large volume of air at the center of the ultrasonic 81000 sensor generated too subjective a height measurement, the "sensor heights" in appendix A were measured from the ground to the top of the sonic black box of electronics. From this point of the black box to the sensor's center point was an additional ~0.32 m of height. The sum of these two values was 2.5 m AGL. The ground above which these sensors were placed was not entirely flat; therefore, the ground type (gravel or pavement) was noted in the appendix A tables.

The spacing between sensors ranged from 1 to 2 m. This distance was based on the standard "2.5 times the obstacle" mounting rule-of-thumb for sensors. A conservative measure of the obstacle (sonic) width was about 28 cm.

The assigned position for each of the 27 sonics is documented in table 1. For a numerically ordered list of the sonics and their Pre- and Post-Calibration position assignments, see appendix B.

Table 1. Pre-calibration sonic position assignment.

Calibration Site Numbering Sequence	Pre-Calibration Group I Sonic	Pre-Calibration Group II: Sonic	Pre-Calibration Group III: Sonic
1- North Wall Side	1330[b]	1360[a]	0637[a]
2	1338	1358	1371
3	1342	1359	1372
4	1343	1361	1373
5 – Sonic Standard	1341[a]	1341[a]	1341[a]
6	1353	1362	1375
7	1354	1368	1376
8	1355	1369	1377
9	1356	1370	1370
10 – South Wall Side	1357[a]	1374[a]	0638[a]

[a]Sonic was sent to a wind tunnel for calibration against a NIST standard just prior to the field study.
[b]Sonic 1330 was the standard used for the *W05US*.

For additional discussion on the sonic positioning within the lateral array, see section 3.

2.2.2 Pre- and Post-*W07US* Sonic Calibration Data Processing

The Pre- and Post-*W07US* calibration data processing phases consisted of three parts: the Qualitative Assessment of the calibration data, the Time Synchronization, and the Quantitative Comparison (relative calibration).

The Qualitative Assessment of the calibration data required the generation of 1-min average time series plots for each uncalibrated sensor as well as the reference (standard) sensor. Data were then reviewed for familiarity, dropouts, trends, systematic bias, etc. Finally, one portion of the Qualitative Assessment was assigned to each team member. The four individual assessment results were qualitatively calibrated against the seasoned-professional's results of our emeritus team member (representing 50 years of micrometeorology experience), who had completed the initial pre-*W07US* sensor evaluation prior to the construction of the *W07US* field study towers and sensor mounting.

The Time Synchronization required the alignment of all sonic output data to a standard 1-min average duration. Long, short, and duplicate minutes were flagged and resolved. Section 3 elaborates on the implementation of this part.

The Quantitative Comparison (relative calibration) employed the time-aligned data filtered for wind tunnel scenarios only. Relative calibration differences for each minute of qualifying data were calculated, tabulated, and averaged. Finally, the quantitative comparison results were submitted for evaluation. Section 3 expounds on the quantitative comparison implementation.

2.2.3 Comparing Pre-*W07US* and Post-*W07US* Sonic Calibration Results

Three foundational comparisons were included in the fourth calibration data processing milestone. First, the most fundamental comparison was the sonic-in-question versus the standard sonic. Second, an evaluation of the averaging duration was investigated. And finally, the Pre- and Post-*W07US* calibration data processing results were compared for biases, trends, etc.

2.2.4 Applications and Documentation

The final two milestones in the calibration data processing were applying and documenting results. Standard protocol requires the original main dataset (raw data) to remain untouched by any Post-*W07US* activities, such as calibration data processing. Instead, if the calibration results indicate that there is a systematic error present and this error is fixable, then a new "dated and documented" Post-*W07US* main dataset is generated. This protocol is especially useful should future data concerns discover that another type of correction is needed, or that the "fix" for the original concern should be handled differently.

The documentation of the calibration data processing results is the function of this report.

3. Calibration Data Processing Method Implementation

As explained earlier, the *W07US* calibration dataset was about 20 GB in size. The Pre-*W07US* sonic dataset was composed of about 12 GB. The Post-*W07US* sonic dataset was composed of about 8 GB. Data files were stored in 1-h increments and organized by the local 24-h day (midnight to midnight).

Milestone I was the acquiring of calibration data from a lateral sonic array (simulating a NIST wind tunnel calibration). Section 2 described the physical layout for the lateral sonic array and the strategic ordering of key sonics for each calibration run. Ten sonics were subjected to calibration at one time. With 25 sonics required for the *W07US*, a minimum of 3 calibration runs were executed. All runs placed the same pre-selected standard sonic in position 5 (nearest to the center). The same data logging system was utilized for both the Pre- and Post-*W07US* Calibration efforts.

Appendix A documents the lateral array sonic position number, data acquisition dates by group, and the vertical and horizontal positions for each mounted sonic.

In the following subsections, the processing of the Pre- and Post-*W07US* sonic calibration data is described. A summary of the calibration results concludes this section.

3.1 *W07US* Calibration Data Preparation

The *W07US* calibration data preparation was accomplished by addressing the systematic data errors and anomalies first. The following sections explain some of the error and anomalies that were addressed.

3.1.1 Error Flags and Missing Data

Calibration data samples from all sensors included an error flag. When the flag was 0, then the sensor was operating properly during the sampling time period. Non-zero flags indicated that the sample data were not reliable. When computing averages, all data errors needed to be filtered, and the number of invalid samples was recorded for each hour processed. Error codes were compared against the character string “0” rather than a numerical value. These errors could be caused by either internal problems or external interference. The error code did not identify the exact cause. Observation of error patterns showed recurrent errors in a few sensors when temperatures were near freezing, indicating a likely flaw in soldering or connectors inside those sensors. Outside of these low temperature events, non-zero error flags occurred in less than 0.01% of all samples.

In addition to error flags, occasional gaps in the data were observed. These regions of missing data occurred due to system outages caused by various issues such as system maintenance, operating system failures, and power outages.

3.1.2 Duplicate Time Stamp Cases and Their Resolutions

Time stamps were applied to each calibration data sample as it was written to disk. The time stamp was based on a system clock, which was synchronized with a central server using Network Time Protocol (NTP). During the occasional network interruption, the system time could drift from the central server. If this drift was more than a few seconds, the NTP client would reset the system time to synchronize with the central server upon reestablishment of network connectivity. This action resulted in discontinuities in the time stamps, with time stamp values jumping forward or backward. These discontinuities occurred rarely, and the largest offsets were less than 30 s. In the case of the time stamp values jumping backward, time stamps would overlap for a short period of time. When calculating averages during these time periods, the “extra” overlapping data were included in the next average period computed. Forward jumping time stamps required no changes and they were taken at face value.

3.1.3 Time Synchronization and Time Stamp Alignments

Calibration data analysis was performed using averaged values. These averages were calculated over a time period evenly divisible into 1 h, namely 1-min averages. All data between the start and end of each time period were averaged, and the midpoint of that time period was assigned as the averaged data’s time stamp. All time stamps were recorded in decimal hours (dec hr) from local midnight. For example, the first average of the 0600 h file would be 06.000000 to

06.016667 dec hr. The time stamp for this averaged minute would be 06.008333 dec hr. In the format of “hours:minutes:seconds”, the first average of the 0600 h file would be calculated using data from 6:00:00 to 6:00:59.9999. The averaged minute would be time stamped as 6:00:30. This process ensured that time stamps for each sensor were synchronous.

3.2 Verification of Key Calibration Equations

An independent verification of the key calibration equations was conducted with the use of Microsoft Excel. This verification was executed for two reasons: first, to independently confirm that critical equations were correct and second, to develop user-friendly tools for future data processing efforts.

3.2.1 Time Averaging Equation, Method and Results

A time averaging equation verification template was constructed, which ingested raw sonic data that had been sampled at a rate of 20 Hz. These data included u-component (U), v-component (V), w-component (W), temperature (Temp), speed of sound (SOS or c), and an error flag. Figure 4 shows a sample layout of the template. At the bottom of each column, a standard averaging equation was added.

Meteorological values for plots. SLOW
ROB 050607

Time	U	V	W	Temp	SOS	Error
10	-2.01	1.04	-0.17	14.52	340.48	0
10.00002	-2.01	1.04	-0.17	14.52	340.48	0
10.00003	-1.89	0.99	-0.13	14.54	340.48	0
10.00004	-1.89	0.94	-0.19	14.49	340.46	0
10.00006	-1.9	0.77	-0.23	14.52	340.48	0
10.00007	-2.08	0.77	-0.16	14.49	340.46	0
10.00009	-2.14	0.73	-0.16	14.61	340.52	0
10.0001	-2.04	0.83	-0.01	14.61	340.52	0
10.00011	-1.98	0.8	0.06	14.62	340.54	0
10.00013	-1.89	0.7	0.09	14.54	340.48	0
10.00014	-2.1	0.72	-0.04	14.49	340.46	0
10.00016	-2.01	0.73	-0.08	14.52	340.48	0
10.00017	-2.06	0.79	0.01	14.47	340.44	0
10.00018	-2.06	0.79	0.01	14.47	340.44	0
10.0002	-1.88	0.69	0.02	14.47	340.44	0
10.00021	-2.05	0.74	0.1	14.52	340.48	0
10.00022	-1.97	0.74	0.02	14.52	340.48	0
10.00024	-1.87	0.74	-0.07	14.52	340.48	0
10.00025	-1.9	0.77	-0.23	14.52	340.48	0

Figure 4. Time averaging equation verification: A sample of the slow velocities template.

Once the basic averaging template was constructed, columns for the wind speed (WS), maximum WS, minimum WS, and WD cells where added. Figure 5 shows these added cells. The spreadsheet equations used to derive the number for each calculated variable have been inserted into the figure in place of the cell's resultant numbers.

C	WS	MAX WS	MIN WS	WD Deg
=(F####)	=SQRT(M#^2+N#^2+O#^2)	=MAX(H#:H####)	=MIN(H#:H####)	=DEGREES(ATAN2(N#,M#))+180

Figure 5. Time averaging equation verification: Additional columns showing the calculated variables—WS, WS statistics, and WD direction. The equations used have been inserted in place of the numbers generated by these equations.

Three different types of WS conditions (fast, slow, and variable) were selected to challenge the method of calculation. A minimum of 5 min were included with each velocity type. The sensor data selected for this verification exercise was the calibration standard (sonic #1341).

The "fast" velocity type utilized westerly winds between 8 and 10 m/s (2007 February 24, 0600–0605 LT). The 5 min of data utilized by the "fast" case were sequential. The "slow" velocity conditions were easterly between 1.2–2.7 m/s (2007 April 11, 1000–1005 LT). Within the "slow" case there was a one 1-min average that fell below the 1 m/s requirement. Therefore, to meet the required 5-min period, the case was extended 1 min, covering a total period of 6 min (while utilizing 5 min for the case study). The "variable wind" type was sampled on 2007 April 16 (1700–1705 LT) and contained westerly winds ranging from 2.4–11.2 m/s. The 5-min "variable" case utilized sequential minutes.

Results from all three WS conditions were the following (Vaucher, 2007a):

- The greatest time average differences were between ±0.000020 dec hr. For perspective, a 1-s sample equals 0.000278 dec hr. So, the time difference was less than two twentieths of a second (two 20 Hz samples). This difference was understood to be due to a decimal-place limitation in the processing computer system.
- All variable average differences were less than or equal to 0.005 variable units, which when rounded to the required two digit decimal, showed a zero differential.

Thus, we found from this portion of the verification effort that the only differences between the original averaging calculations in C++ and those from the independent verification in Excel, were insignificant and could be attributed to machine/software limitations and rounding errors.

3.2.2 Relative Calibration Equation, Method and Results

Once the various averaging equations were verified, the next critical equation targeted for an independent verification was the relative calibration equation. In the formula's most basic format, this equation subtracted the standard-sonic value from the value of the sonic being calibrated (equation 3):

$$\text{delta} = \text{uncalibrated sonic} - \text{calibrated sonic} \tag{3}$$

Mathematically speaking, a positive delta value indicated the uncalibrated sonic had overestimated the calibrated sonic value; whereas, a negative delta indicated an underestimation of the calibrated sonic unit. Unfortunately, sonic u, v, and w components use their plus and minus signs to also indicate spatial direction. This potential conflict of sign usages was addressed in the discussion over the final calibration result interpretation; however, for the purpose of equation verification, the interpretation followed the simple relationships described in table 2.

Table 2. Interpretation of delta (equation 3).

Uncalibrated Data	Calibration Data	Delta Data (Equation 3)	Interpretation of Results
2	2	0	Identical
1	2	-1	Underestimate
3	2	1	Overestimate
-2	-2	0	Identical
-3	-2	-1	Underestimate
-1	-2	1	Overestimate
-2	2	-4	Underestimate
-1	2	-3	Underestimate
-3	2	-5	Underestimate
2	-2	4	Overestimate
3	-2	5	Overestimate
1	-2	3	Overestimate

Once the deltas were calculated, the initial results would be used to identify systematic errors, biases, etc. Later, when the actual test data were being prepared for analysis, corrections to the errors, biases, etc., could be applied.

The method for verifying the relative calibration equation required an Excel *Delta Calculation* workbook that was much larger than the previous 1-min average workbook. This increased file size was a consequence of having to document all of the filter processing steps.

The verification effort began by first converting the calibrated and uncalibrated 1-min average data from text files into Excel file formats. The two sonics selected for the verification task were the calibration standard sonic (1341) and the uncalibrated sonic (1361). Next, a *SonicData* worksheet was created that subtracted the calibrated from the uncalibrated sonic data to give the deltas for all 1-min average values.

The *FilteredWDResults* worksheet used the 1-min averages from the *SonicData* sheet and filtered out data with WDs that were not between 240–300° (westerly) and 60–120° (easterly). The worksheet then compared the qualifying westerly and easterly data of the reference sonic against the same for the uncalibrated sonic. An excerpt of the *FilteredWDResults* worksheet is shown in figure 6.

WD from 240-300 (Deg) - Time in	Qualifying Minutes - Yes = 1	WD from 60-120 (Deg) - Time in	Qualifying Minutes - Yes = 1	WD from 240-300 (Deg) - Time in	Qualifying Minutes - Yes = 1	WD from 60-120 (Deg) - Time in	Qualifying Minutes - Yes = 1	Qual West Wind - Time in	Qualifying Minutes - Yes = 1	Qual East Wind - Time in	Qualifying Minutes - Yes = 1
1341	-	1341	-	1361	-	1361	-	-	-	-	-
57.00035	1	0	0	57.00035	1	0	0	57.00034721	1	0	0
57.00104	1	0	0	57.00104	1	0	0	57.00104167	1	0	0
57.00174	1	0	0	57.00174	1	0	0	57.00173613	1	0	0
57.00243	1	0	0	57.00243	1	0	0	57.00243054	1	0	0
57.00313	1	0	0	57.00313	1	0	0	57.003125	1	0	0
57.00382	1	0	0	57.00382	1	0	0	57.00381946	1	0	0
57.00451	1	0	0	57.00451	1	0	0	57.00451388	1	0	0
57.00521	1	0	0	57.00521	1	0	0	57.00520833	1	0	0

Figure 6. The *FilteredWDResults* worksheet identified data samples with WDs that were either westerly or easterly.

The next worksheet, called *FilteredWSResults*, took the qualifying data from the WD filter and filtered out points with WSs less than 1 m/s. This threshold velocity was selected to eliminate the random nature of the calm to 1 m/s conditions (Wikipedia, 2008). Figure 7 shows a sample of the *FilteredWSResults* worksheet.

Data Preparation

240-300 Wind Speed (m/s)	240-300 Wind Direction (deg)	60-120 Wind Speed (m/s)	60-120 Wind Direction (deg)	240-300 Wind Speed (m/s)	240-300 Wind Direction (deg)	60-120 Wind Speed (m/s)	60-120 Wind Direction (deg)	Wind Speed Filter Data with WS > 1m/s	Data with WS > 1 m/s
1341	1341	1341	1341	1361	1361	1361	1361	240-300	60-120
8.0079	269.39	0	0	8.1176	267.1	0	0	1	0
5.7621	271.71	0	0	5.9325	268.98	0	0	1	0
6.7383	274.2	0	0	6.6313	270.85	0	0	1	0
6.5703	272.83	0	0	6.8685	269.59	0	0	1	0

Figure 7. The *FilteredWSResults* worksheet identified data samples with wind speeds greater than 1 m/s.

Finally, a *Delta* worksheet (figure 8) used the *FilteredWSResults* results to determine if the data had met all of the filtering requirements. If so, the *Delta* worksheet transferred the qualifying delta values from the *SonicData* worksheet to itself. If the data did not meet the filter requirements, a "FALSE" was entered into the *Delta* worksheet instead. This FALSE statement was filtered out when calculating the average delta for verification with the C++ program.

1361-1341
deltas statistics

AVERAGE	0	0.148135	0.392412	-0.22943	0.115459	0.068143	0.141287	-2.74659
STD DEV	0	0.24195	0.150221	0.177953	0.056833	0.033878	0.274266	1.120002
MAX	0	0.8396	0.8432	0.2677	0.21	0.12	0.881	8.2
MIN	0	-0.8836	-0.2564	-0.904	-0.06	-0.04	-1.0872	-10.54

1361-1341
deltas statistics

AVERAGE	=AVERAGE(B6:B1445)	=AVERAGE(C6:C1445)	=AVERAGE(D6:D1445)
STD DEV	=STDEVP(B6:B1445)	=STDEVP(C6:C1445)	=STDEVP(D6:D1445)
MAX	=MAX(B6:B1445)	=MAX(C6:C1445)	=MAX(D6:D1445)
MIN	=MIN(B6:B1445)	=MIN(C6:C1445)	=MIN(D6:D1445)

Figure 8. A *Delta* worksheet example of the statistical results and equations.

The numerical results from the relative calibration verification showed differences between the independent C++ and Excel program outputs to be less than E-14 variable units (Vaucher, 2007b). One of the lessons learned while executing this task, was that the detailed *Delta Calculation* workbook was a critical tool in clarifying the C++ program procedural requirements and in verifying that the program was executing the task properly. Finally, we can confidently state that after running the same data through both programs, the final version of the C++ program showed no significant differences in its results to those independently calculated with the Excel program.

3.2.3 Summary

The independent equation-verification exercises were critical in clarifying the C++ program's procedural requirements, as well as confirming that the program was executing the task properly. After reviewing the averaging and relative calibration equation verification results, we determined that the C++ programs showed no significant differences in their results to those independently calculated by the Excel programs. Thus, the relative calibration project was declared ready for the 27 sensor relative calibration data processing calculations.

3.3 Calibration Data Analysis

The relative calibration data analysis began by evaluating several time-averaging lengths for the 20 Hz raw data. The next concern involved the building effects on the data and whether they had a significant impact. Once these issues were resolved, the relative calibration results were examined. Each step is discussed in the subsequent sections.

3.3.1 Averaging Lengths

The calibration data analysis commenced by determining the best averaging length for the data. Throughout the calibration tool development and equation verification, the field standard of a 1-min average had been utilized. The analysis continued with these 1-min averages, extracting only those samples which fit the simulated wind tunnel qualifications from both the Pre- and Post-*W07US* Calibration datasets. The averaged total of qualified samples per sonic was 3115 (±1169). When 5- and 15-min averages were used, the average population of qualified data per sonic totaled 671 and 225, respectively. Table 3 shows the statistical summaries for the qualified 1-, 5-, and 15-min average resources. The severe reduction in population between the 1-min and subsequent length averages was primarily due to the finite number of samples being subdivided into larger portions. The fact that these qualifying samples were slightly higher than the fractional proportion indicates that some favorable smoothing effects were present. The net result for the calibration differences was that the 15-min averages generated a tighter standard deviation than the 1-min average results. This observation elevated the importance of the larger average with respect to the individual sensor data quality statements derived from the calibration analysis. However, before these statements could be formulated, the building effects needed to be addressed.

Table 3. Statistical summary of the 1-min average data resources qualified for the relative calibration calculations.

	Pre- and Post-Calibration Data Resources	**Pre-*W07US* Calibration Data Resource**	**Post-*W07US* Calibration Data Resource**
Qualified 1-min averages			
Average sample number	3115	3385	2846
Standard deviation	1169	1235	1055
Maximum sample number	6539	5599	6539[a]
Minimum sample number	1204	1204	1727
Qualified 5-min averages			
Average sample number	671	737	606
Standard deviation	263	251	264
Maximum sample number	1374	1168	1374
Minimum sample number	285	285	355
Qualified 15-min averages			
Average sample number	225	246	205
Standard deviation	90	85	91
Maximum sample number	474	393	474
Minimum sample number	91	91	120

[a]Sonic 1370 was used in Post-*W07US* Calibration Group II (2343 qualifying samples) and Group III (4196 qualifying samples).

3.3.2 Building Effects

The building effects were addressed by examining the spatial distribution of the qualified 1-min average resources. These were selected due to the greater data population. The analysis presumed that if there was a systematic building effect on the data, the effect would be evident in the number of qualifying samples as a function of the 10 sensors' spatial positions. That is, if the sonics closest to the buildings consistently showed a lesser number of qualified data, then one might presume that the building was contributing to this pattern of reduced qualified resources. The subsequent question would then be, "Is the contribution significant to the calibration analysis?"

The qualified Pre- and Post-*W07US* Calibration data were combined and sorted by their sonic positions. Due to an inconsistent number of days sampled in the Pre-Calibration Groups II and III, this approach had to be revised slightly. (Note: The inconsistent length of data acquisition periods was caused by the natural atmosphere's unregulated availability of strong, consistent westerly or easterly winds during the calibration data acquisition periods, and a 1-time, unexpected Universal Serial Bus (USB) failure.) The sample populations were normalized, using the total possible samples that the sensor would have been able to acquire, as a common denominator. This conditioning meant that if all samples qualified for calibration analysis, the cumulative total for the three Pre- and three Post-*W07US* Calibration groups would be 600% (6.0). Likewise, examining the Pre- or Post-*W07US* Calibration groups separately would generate a maximum total of 300% (3.0) for each calibration set.

Figure 9 shows the cumulative percent of qualified 1-min averages for both Pre- and Post-*W07US* Calibration datasets. For convenience, each group was given a unique bar chart color: Group I sonics are red, Group II sonics are green, and Group III sonics are blue. The light color bars indicate Pre-Calibration groups and the darker colors indicate Post-Calibration groups. The trend in figure 9 shows a gradual increase in magnitudes from position 1 through 4. Position 5 is zero, since that was the location of the standard sonic by which all others were compared. The tapering off of values between positions 6 to 10 is less consistent. This was in part due to some overlapping sampling times. Sonics in positions 7, 8, 9, and 10 experienced some data interruptions during their Pre-Calibration data acquisition days; thus, reducing the total possible samples acquired. The statistics were based on an uninterrupted 60-min hour length.

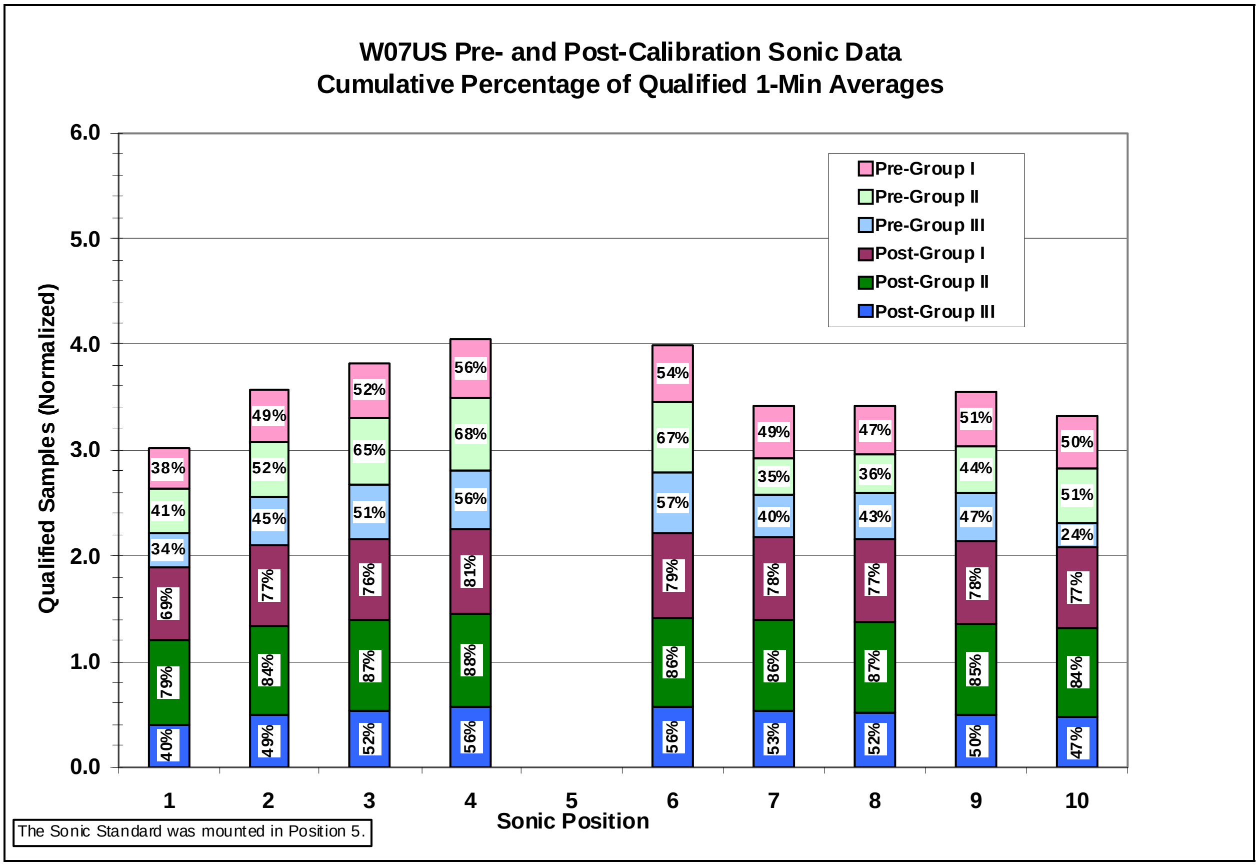


Figure 9. Cumulative percentage of qualified 1-min averages for both Pre- and Post-Calibration datasets.

Since the Post-Calibration data acquisition had no data interruptions, the three group cumulative percentage of qualified 1-min averages provided a clearer picture of any systematic trends (figure 10). Note: To view this chart three dimensionally, see appendix C. Starting from position 1 (near wall) through position 4 (near center flow), there is a gradual 37% increase, which is consistent with figure 9. Positions 6 (near center flow) to 10 (near wall) show a gradual 13% decrease. Clearly some building effect is present, but is this significant to the current analysis?

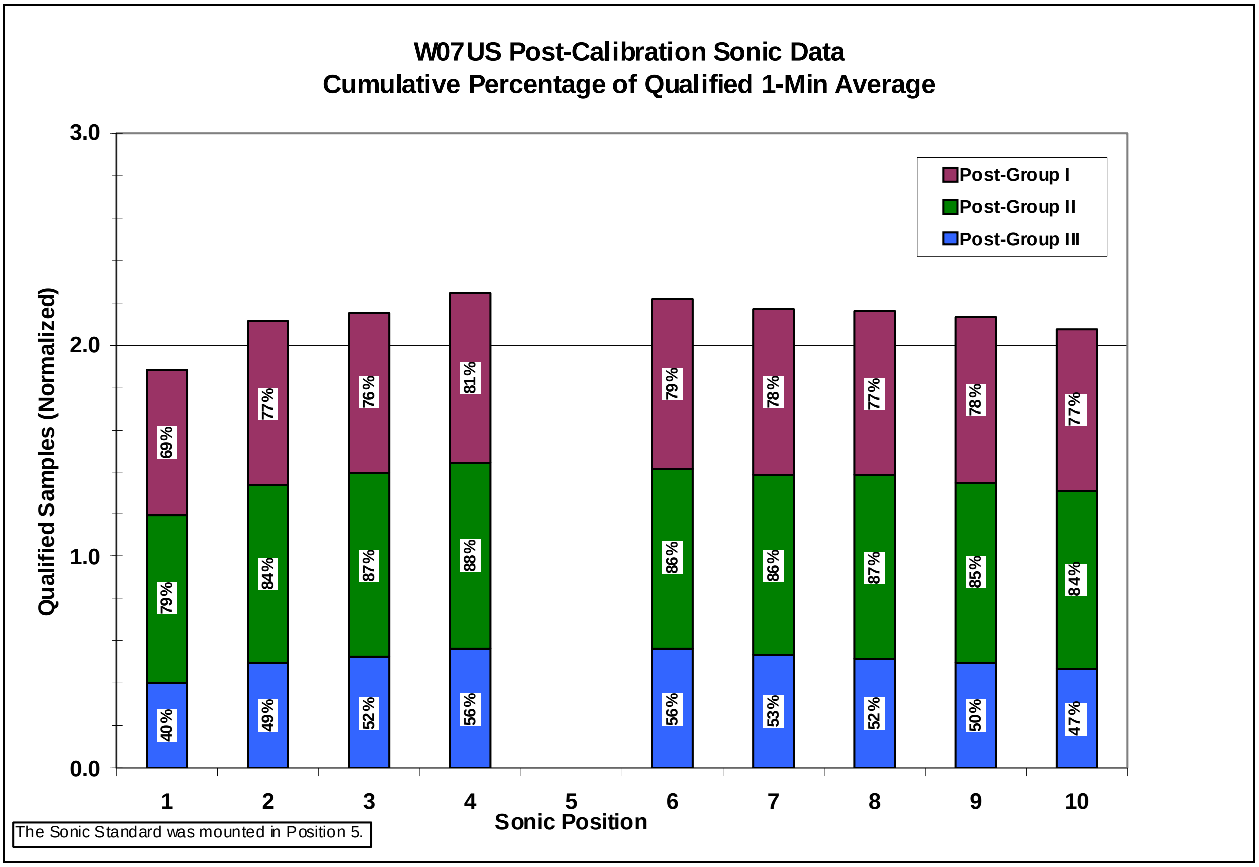


Figure 10. The Post-Calibration group data had no data interruptions and therefore better displays the cumulative percentage of qualified 1-min average trends.

The requirements that wind directions had to be westerly, and above 1 m/s, were used to most closely simulate a tunnel environment. Since the magnitude of qualifying samples ranged from 1204 through 6539, with the average as 3115, the consensus was that the building effect impact on the qualified sample resources was not significant enough to bias the results. There was also a decision that, while the 15-min averages produced smaller standard deviations, the more-populated array of 1-min averages needed to be consulted first when evaluating the relative calibration results (due to the larger resource population).

In sections 3.3.3 and 3.3.4, the Pre- and Post-*W07US* Calibration results will be presented separately. The combined observations will then be highlighted in section 4.

3.3.3 Pre-*W07US* Calibration Differences

The Pre-*W07US* calibration was executed in three sequential data acquisition sessions. Table 4 shows the time table for each group. As mentioned earlier, the length of days for each group's data acquisition varied. While this inconsistency was partly due to a Pre-*W07US* hardware failure, the primarily cause was a function of accomplishing the mission objective. That is, each group needed to acquire data long enough for the atmosphere to simulate wind tunnel calibration

conditions (consistent, strong westerly or easterly winds). Once these conditions were met, then the next sonic group was installed for calibration. For the Pre-Calibration, the data acquisition periods ranged from 74–142 h and averaged 110 h (about 4.5 days).

Table 4. Pre-*W07US* calibration group time tables.

Pre-Calibration	Dates (2007)	Julian Days	Time Length (Decimal Days)	Total Possible Minutes
Group I	Feb. 16–21	47–52	4.8333	6960
Group II	Feb. 21–27	52–58	5.7083	4440
Group III	Feb. 27–Mar. 5	58–64	5.9167	8520

As described earlier, each of the 27 sonics was assigned a position in the 10-mount alignment. Table 5 documented these assignments and appendix B provides a numerically ordered list of the sonics and their position assignments.

Table 5. Pre-*W07US* calibration sonic position assignment.

Calibration Site Numbering Sequence	Pre-Calibration Group I Sonic	Pre-Calibration Group II: Sonic	Pre-Calibration Group III: Sonic
1- North Wall Side	1330[b]	1360[a]	0637[a]
2	1338	1358	1371
3	1342	1359	1372
4	1343	1361	1373
5 – Sonic Standard	1341[a]	1341[a]	1341[a]
6	1353	1362	1375
7	1354	1368	1376
8	1355	1369	1377
9	1356	1370	1370
10 – South Wall Side	1357[a]	1374[a]	0638[a]

[a]Sonic was sent to a wind tunnel for calibration against a NIST standard just prior to the field study.
[b]Sonic 1330 was the standard used for the *W05US*.

The specifications of sensor heights and the distances between sonics and the buildings were recorded and are included in appendix A. The ideal sensor height was 2.5 m AGL and the average spacing between sensors ranged from 1 to 2 m. The distance from the northern building's wall was about 4.30 m; from the southern building's wall was about 9.0 m.

The initial calibration differences examined were u-, v-, and w-components. The 1-min Pre-*W07US* Calibration differences (delta (Δ)u, Δv, Δw) are plotted in figure 11. Sonic data for Group I was plotted in their north to south positions, and labeled 1 through 10; Group II was plotted in positions 11 (north side) through 20 (south side); and, Group III was plotted in positions 21 (north side) through 30 (south side). Positions 5, 15, and 25 were zero in all groups, since these were where the standard was placed.

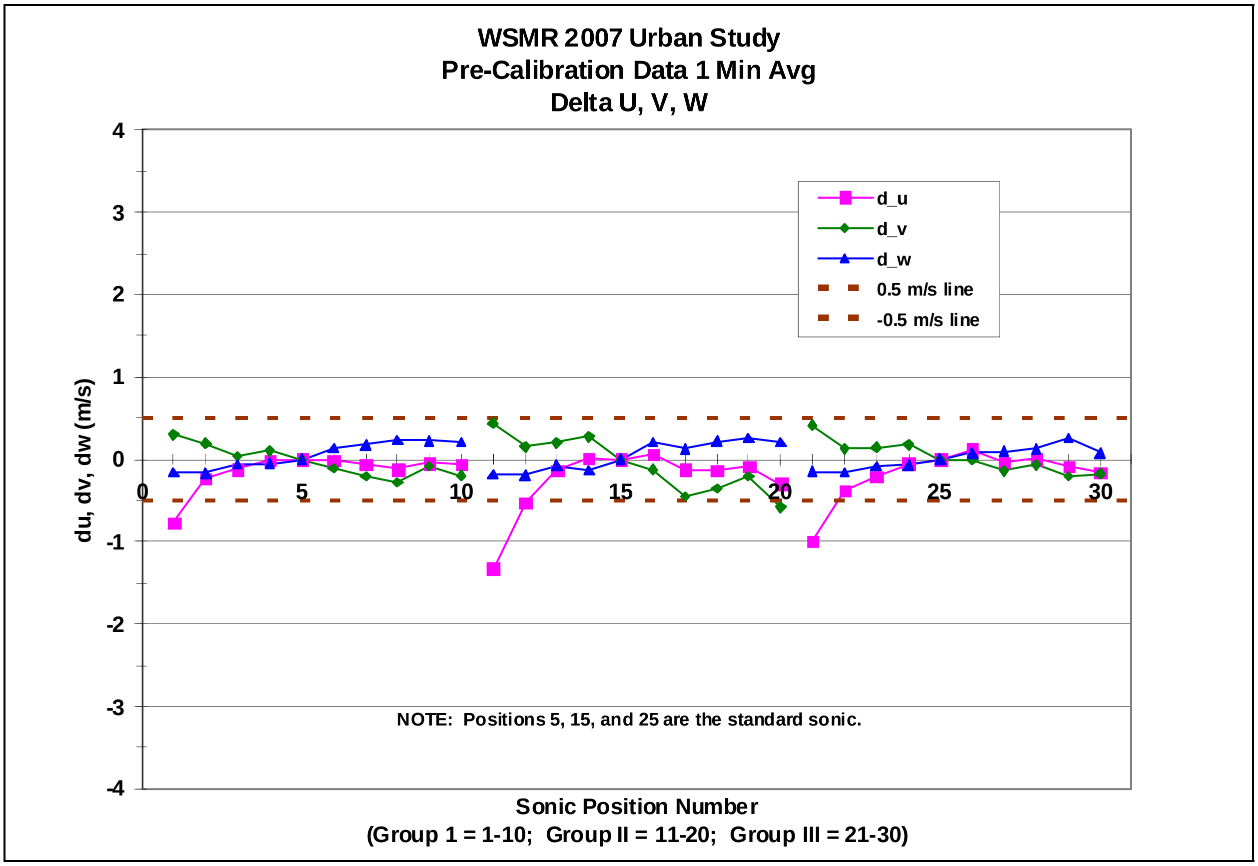


Figure 11. The 1-min Pre-*W07US* Calibration differences for the component winds (Δu, Δv, Δw).

The overall Pre-*W07US* calibration difference trends for each component were consistent for each component. Δu (red markers and line) underestimated the calibrated standard between positions 1 through 4, with the greatest underestimated values in positions 1 and 2; position 5 was the standard and was zero; position 6 very slightly overestimated the standard, then positions 6 through 10 slightly underestimated the values.

The Δv results (green markers and line) showed slightly overestimated values between positions 1 through 4. Position 5 was zero (the standard). From positions 6 through 10 the underestimation of the standard gradually increased.

The Δw results (blue markers and line) from positions 1 through 4 slightly underestimated the standard. Positions 6 through 10 slightly overestimated the standard.

Numerically, all but three 1-min Pre-Calibration difference values were less than ±0.53 m/s. These three values were in position one of each group for the Δu results (closest to the building, on the north side of the line up). Because of the consistent disproportionately large underestimation of position one from each Pre-Calibration group, followed by positions 2 and 3 showing values more in keeping with the other findings, one must suspect that the building's effect on the flow may outweigh the criteria imposed for simulating a wind tunnel environment.

The position 1 disproportionate values were also observed in the 15-min averaged Pre-Calibration differences.

3.3.4 Post-*W07US* Calibration Differences

The Post-*W07US* calibration was executed in three sequential data acquisition sessions. Table 6 shows the time table for each group. The variable length of days was primarily a function of the need for strong wind events to simulate wind tunnel conditions over the data acquisition site and administrative logistics (couldn't schedule work over weekends). No hardware failures occurred during this data collection period. The data acquisition duration ranged from 42–140 h, with the average being 76 h (3.2 days).

Table 6. Post- *W07US* Calibration group time tables.

Post-Calibration	**Dates (2007)**	**Julian Days**	**Time Length (Decimal Days)**	**Total Possible Minutes**
Group I	April 9–11	99–101	1.7500	2520
Group II	April 11–13	101–103	1.9167	2760
Group III	April 13–19	103–109	5.8333	8400

Though there were no changes in the sonic positions (table 7), the sonic list by group number and position for the Post-*W07US* Calibration is included for convenience. Note: Appendix B contains the same list reorganized in numerical order.

Table 7. Post- *W07US* calibration sonic position assignment.

Calibration Site Numbering Sequence	**Post-Calibration Group I Sonic**	**Post-Calibration Group II: Sonic**	**Post-Calibration Group III: Sonic**
1- North Wall Side	1330[b]	1360[a]	0637[a]
2	1338	1358	1371
3	1342	1359	1372
4	1343	1361	1373
5 – Sonic Standard	1341[a]	1341[a]	1341[a]
6	1353	1362	1375
7	1354	1368	1376
8	1355	1369	1377
9	1356	1370	1370
10 – South Wall Side	1357[a]	1374[a]	0638[a]

[a]Sonic was sent to a wind tunnel for calibration against a NIST standard just prior to the field study.
[b]Sonic 1330 was the standard used for the *W05US*.

The sensor height was 2.5 m AGL and the average spacing between sensors ranged from 1 to 2 m. The Post-*W07US* calibration distance from the northern building's wall to position 1 was about 4.55 m; from the southern building's wall to position 10 was about 9.2 m. For additional information regarding sensor location specifications, see appendix A.

The 1-min Post-*W07US* Calibration differences (Δu, Δv, Δw) are plotted in figure 12. Sonic data was grouped as before with Group I sonics plotted in 1 (north side) through 10 (south side); Group II plotted in positions 11 (north side) through 20 (south side); and Group II plotted in positions 21 (north side) through 30 (south side). Position 5, 15, and 25 are zero, since these were where the standard was placed.

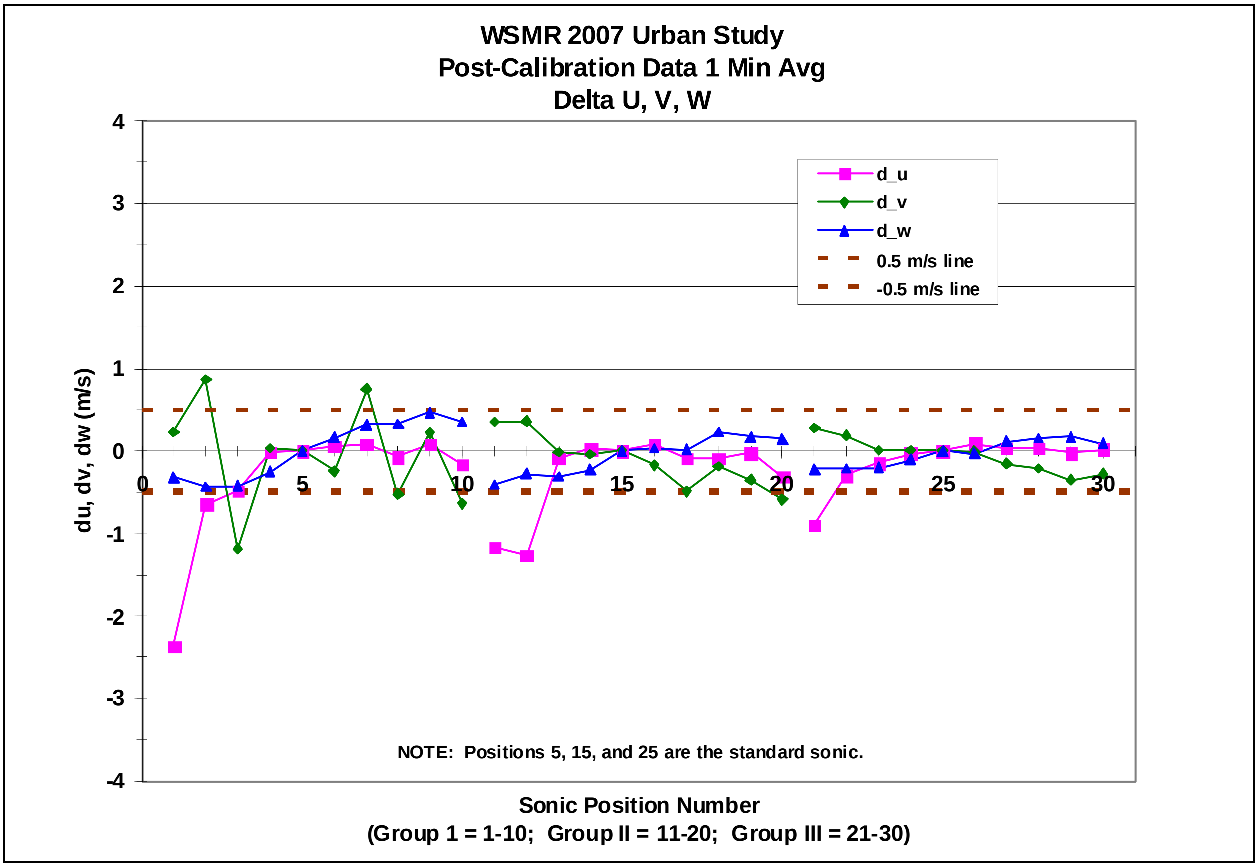


Figure 12. The 1-min Post-*W07US* Calibration differences for the component winds (Δu, Δv, Δw).

The overall trends for each Post-*W07US* Calibration component were similar, but not identical to, the Pre-*W07US* Calibration results. The Δu (red markers and line) underestimated the calibrated standard between positions 1 through 4, with the greatest underestimated values in positions 1 and 2. Position 5 was the standard and was zero. From positions 4 through 9 the magnitude of differences tightly hovered around the zero line. Position 10 of Group III closely matched the zero line. Groups I and II position 10 slightly underestimated the standard.

The Post-*W07US* Calibration Group II and Group III Δv results (green markers and line) presented a pattern similar to the Pre-*W07US* calibration results. Positions 1 and 2 slightly overestimated the standard. Positions 3 and 4 tightly matched the zero line. Position 5 was zero (the standard). From positions 6 through 10, the results showed an underestimation of the standard. All differences in the underestimation were between 0 and -0.6 m/s.

Group I Δv results (green markers and line) had three outliers in positions 3, 7, and 10. Apart from these sensors, the trend remained with the first two positions overestimating the standard, position 4 aligns with the zero line, and positions 6, 8, and 10 showed an increasing underestimation. Position 9 hovered near the zero line and was, therefore, not a concern. Position 7 showed an overestimation of the standard in contrast to those sensors surrounding it. The Group I position 3 sonic presented an uncharacteristically large underestimation not found in the Pre-*W07US* Calibration results.

The Post-*W07US* Calibration Δw results (blue markers and line) align well with the Pre-*W07US* Calibration results. Positions 1 through 4 underestimated the standard. Positions 6 through 10 hover over the zero line, in general, tending to overestimate the standard.

Numerically, if positions 1 and 2 were ignored, the rest of the 1-min Post-*W07US* Calibration results were less than ±0.5 m/s. Observing Post-*W07US* Calibration Group III's initial two positions, they follow the pattern observed in the Pre-*W07US* Calibration data. That is, the initial two Δu values, of about 0.9 m/s and 0.3 m/s respectively, underestimate the standard. Group III's Δv and Δw also follow the Pre-*W07US* Calibration pattern.

Post-*W07US* Calibration differences for Groups I and II positions 1 and 2 appear to be disproportionately underestimating the standard. This pattern was also observed in the 15-min averaged Post-Calibration differences.

4. Discussion of Results

The data resources for the Pre- and Post-*W07US* calibration are summarized in figure 13. The minimum number of qualified calibration samples taken before and after the *W07US* was greater than 1200 and the maximum was less than 6540. Six of the sensors had been calibrated against a NIST standard about 2.5 months prior to the field study. One of these NIST calibrated sensors was used as the standard against which all the other 26 sonics were compared.

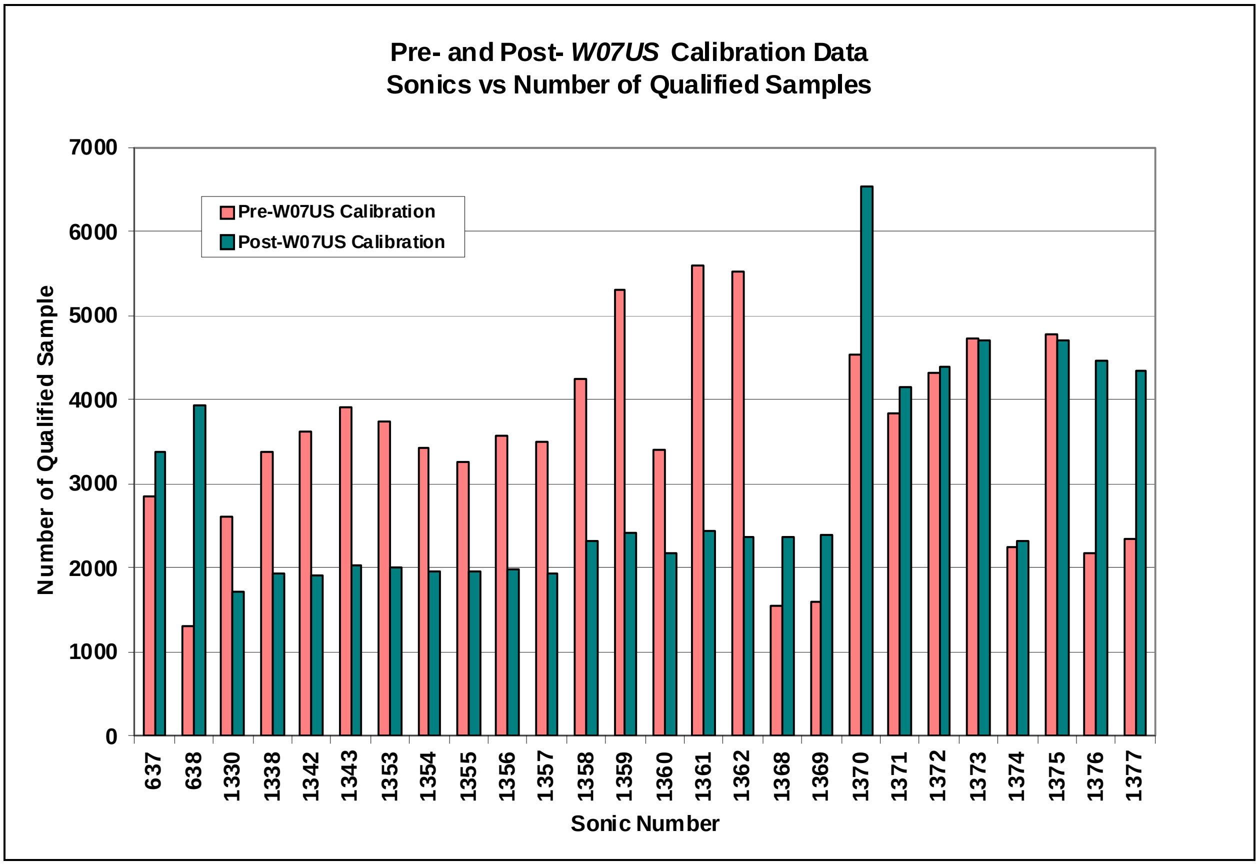
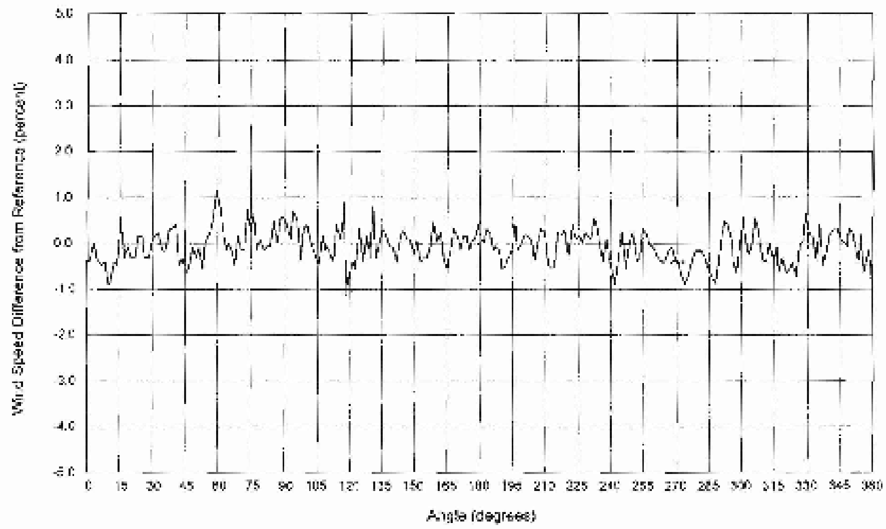


Figure 13. A histogram of the Pre- and Post-*W07US* calibration data resources.

Figure 14 shows the NIST results for the designated *W07US* standard, sonic number 1341. The percentage of WS differences from the NIST reference for the pre-selected 90° and 270° windows, were about +0.5% and -0.5%, respectively. The WS for the wind tunnel calibration averaged 12.33 m/s, with a standard deviation of 0.5 m/s. At these high velocities, wind speed differences were about 0.06 m/s. When a ±30° buffer is added, the percentage value extends to slightly above 1%. The WS difference for this latter percentage is about 0.15 m/s.

R. M. Young Company
Model 61000 Ultrasonic Anemometer
Wind Speed vs. Direction Calibration Record
SN01341 Jan 03 2007



Sensor output: 4Hz.
Sensor rotated from 0 to 360 degrees at 5 degrees/second.
Wind tunnel speed using NIST traceable reference: 12.33 m/s
Sensor Average Speed: 12.32 m/s
Sensor Standard Deviation of Speed: 0.06 m/s

61000 SN01341 1000 RPM Cal Check 01-03-2007-11-55-14.csv

R. M. Young Company, 2801 Aero Park Drive, Traverse City, MI 49686 USA
CK61000

Figure 14. The NIST results for the designated *W07US* standard, sonic number 1341.

When the standard sonic (#1341) was evaluated for data with velocities exceeding 12 m/s, the Pre-*W07US* Calibration sonic Group I dataset reported 5 qualifying data points. Lowering the wind speed threshold to 10 m/s, the Group I data points available from the standard totaled 46. Since this analysis was the first detailed inspection for many of the sensors, the decision was made to align with the concept that the greater the statistical population resource, the more representative the result. Therefore, a 1 m/s threshold was defined. This liberal acceptance of values was also appropriate in light of the atypical seasonal wind conditions encountered during the *W07US* calibration periods. Strong winds were expected based on the climatological reports, but unfortunately, they didn't always manifest in a timely manner and lower velocities had to be accepted for the local relative calibration efforts. Consequently, as the lighter winds occurred, the potential for larger calibration differences also increased. The results were described in the previous sections.

A systematic pattern of underestimating Δu and overestimating Δv was observed in sonic positions 1 and 2. Since the position 1 sonics had been independently subjected to a NIST calibration just prior to the field study, the presumption was that these sensors were still functioning correctly and the observed offsets were due to the building proximity (local forcing effects). Regarding the sonics in position 2, there was an observed trend in the results for sensors from the northern most position 1 through position 3 (near the center). This trend showed large difference values near the north wall that reduced to the more expected magnitudes (hovering around zero) around position 3. For this reason, position 2's results were considered inconclusive. That is, the building induced airflow pattern had sufficiently disrupted the sensors' ability to provide acceptable results. Hence, the consensus was to "ignore" the systematic offsets suggested by the position 1 and 2 results, and transfer the experience over to the "lessons learned for future calibration designs" category.

Within this "lessons learned" category were put the following observations that might assist in explaining the building effects impacting positions 1 and 2 of the lateral sonic array: First, in section 3.3.2 (building effects), a gradual 37% increase was noted between positions 1 and 4, and a 13% decrease was noted between positions 6 to 10. Putting these together, one might say that the north side trend was about 2.8 times that of the south side. Next, note that the distance between position 1 and the northern building was 4.3 m. The distance between position 10 and the southern building was 9.0 m. Thus, the north side was about 2.1 times closer to the building than the south side. These concepts coupled with the fact that the north building was about twice the height (and about half the length or fetch) of the south building may help to explain the over- and underestimations of results in the first two positions of the sonic lateral array (Szymber, 2008).

After assimilating the results from the three Pre-*W07US* Calibration groups, Post-*W07US* Calibration Groups II and III, and removing any results from the positions 1 and 2 sonics (due to the local forcing influences explained earlier), the following observations were made:

1. Pre- and Post-*W07US* Calibration Groups II and III calibration differences stayed between ±0.5 m/s. Pre-*W07US* Calibration Group I also stayed between ±0.5 m/s.
2. All three Pre-*W07US* Calibration Groups stayed between ±0.3 m/s (without including positions 1 and 2 in the results).
3. Δu pattern: The positions 1 through 10 Δu pattern included an underestimation of the standard from positions 1 through 4 (north side of the standard), then hovered around the zero line for positions 6 through 10.
4. Δv pattern: The systematic Δv pattern showed a downward trend between positions 1 and 10. The overestimation of the standard in positions 1 through 4 decreased in magnitude then began to increasingly underestimate the standard between positions 6 and 10.
5. Δw pattern: Δw was opposite Δv. The Δw underestimated the standard on the north side of the standard (positions 1 through 4), then ever so slightly, increasingly overestimated the standard between positions 6 through 10.
6. The placement of the standard (position 5) was the ideal location. This statement was based on the consistent "mid-stream" character observed in the Δu, Δv, and Δw trends.

The next step was to examine the relative calibration results for WS and WD. Figure 15 shows each sonic and its averaged WS calibration difference. The sonics most vulnerable to local forcing were the NIST calibrated sonics, which were located nearest to the buildings. These are flagged with an asterisk and listed in the figure's graphical note. Ignoring the 6 flagged sonics, 78% of the remaining sonics were within ±0.15 m/s of the standard. Such values align with the Pre-*W07US* wind tunnel NIST results from figure 14. The distribution of results within this 78% included 48% of the sonics reporting a slight overestimation of the standard and 30% reporting a slight underestimation.

Examining the underestimated results more closely, when an underestimation occurred, the value was less than 0.5 m/s. The two outlying sonics to this observation, numbers 1358 and 1342, still showed acceptable underestimation values for the Pre-*W07US* Calibration (≤0.56 m/s). Their Post-*W07US* Calibration differences showed an increased underestimation of 0.71 and 1.22, respectively.

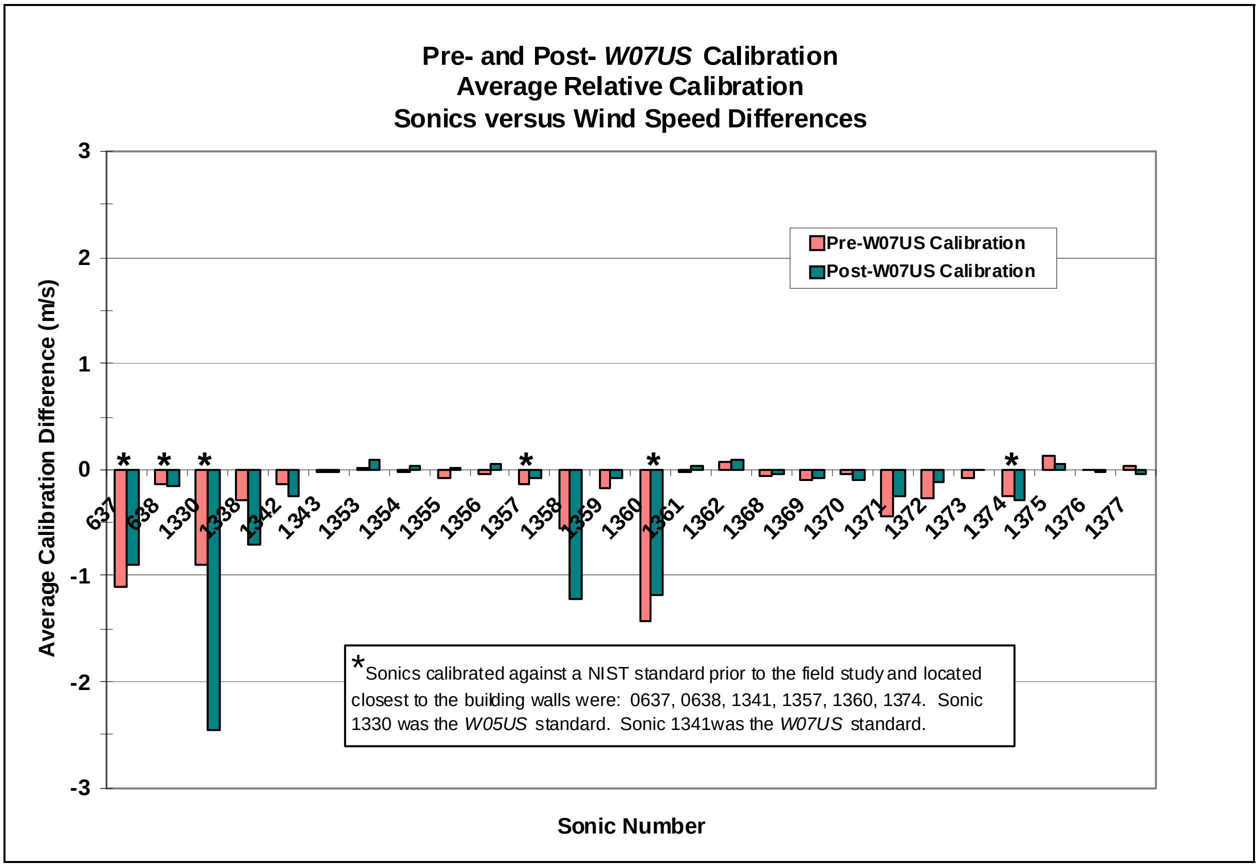


Figure 15. Pre- and Post-*W07US* relative calibration WS results.

Wind direction differences were calculated and the results are included in appendix D. These results were not extensively analyzed, since restrictive WD requirements were used to qualify the data for the analysis. An interesting observation, however, is that five of the six sonics closest to the building aligned well (<±3°), with the standard mounted in the middle of the building canyon. For numerical results, see appendix E.

Returning to the component wind results, figures 16 and 17 show all components side-by-side for each sonic. Ignoring the asterisk sonics for reasons explained earlier, the remaining sonics come close to the 0.35 through -0.5 m/s window. When these thresholds are exceeded (1338, 1342, 1354, 1357, 1360, 1374), the v-component tends to be the one doing so. The sonics where the u-component exceeds the underestimation threshold include 1338, 1358, and 1360. The only sonic with w-component exceeding the threshold is 1356.

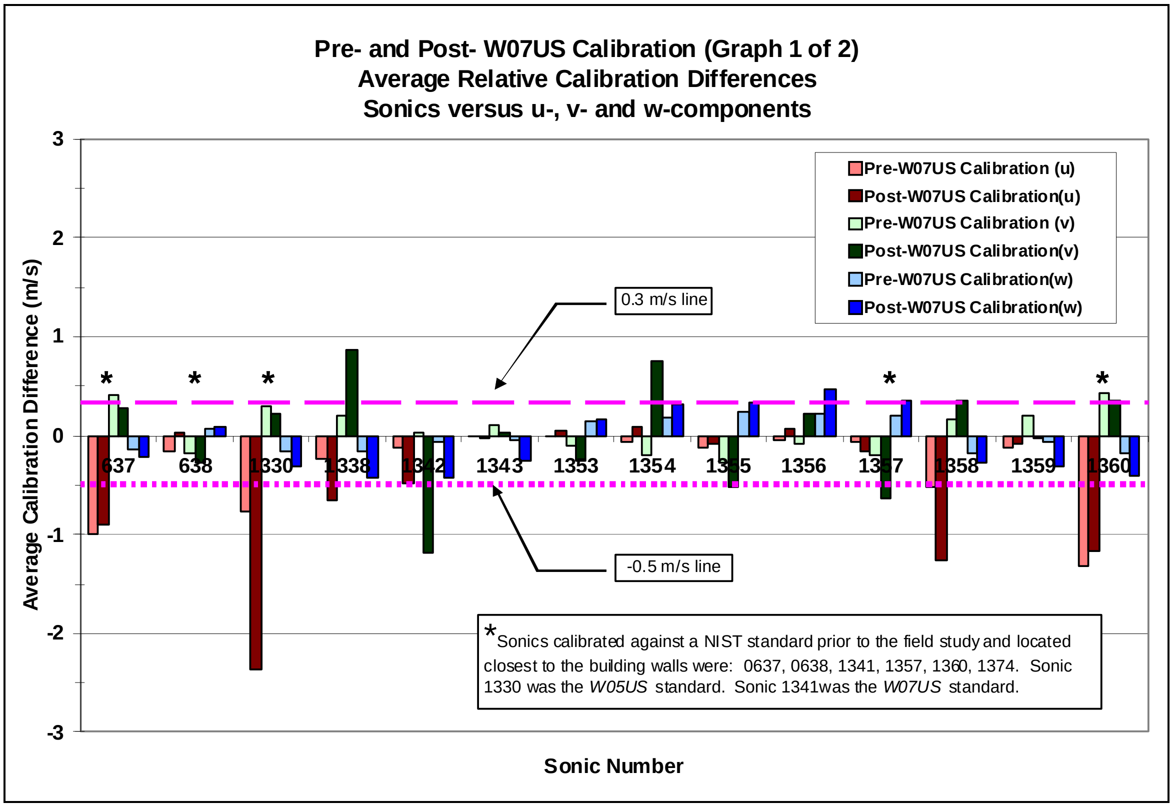


Figure 16. Pre- and Post-*W07US* relative calibration wind component results, graph 1 of 2.

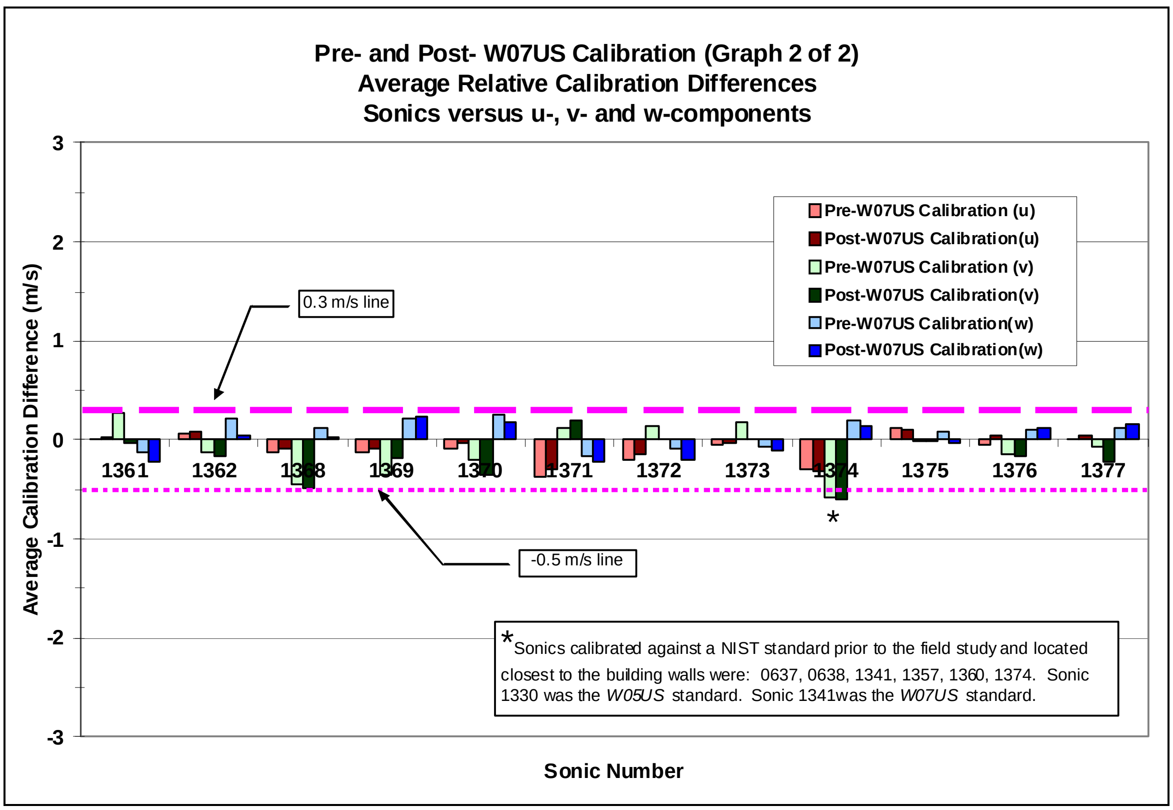


Figure 17. Pre- and Post-*W07US* relative calibration wind component results, graph 2 of 2.

5. Conclusions and Recommendations

Calibrating sensors is an important step in determining the confidence one has in the quality of data acquired. Without access to a NIST wind tunnel facility, side-by-side relative calibration (against a NIST calibrated sensor) is an alternate method for calibrating meteorological sensors. For the *W07US* field study, a Pre- and Post-*W07US* calibration was conducted on the 27 sonics slated for the *W07US* project. These sonics were organized in groups of 10 and mounted in a lateral array between 2 parallel buildings. The same standard sonic, previously calibrated against a NIST standard, was placed in the middle of the arrays. The six sonics most recently calibrated against a NIST standard were placed in the end positions of the lateral array, as these locations were most vulnerable to building airflow effects.

Prior to the data analysis, the calibration data was examined for error flags, missing data, duplicate time stamps, and time synchronization. An independent verification of the time averaging equation, and the relative calibration equation, was conducted to ensure the accuracy of the calibration tools and procedures.

The data analysis examined various averaging lengths for calculating the relative calibration. The two that were included in the interpretation of results were the 1-min averages, which produced the largest population, and the 15-min averages, which displayed the narrowest standard deviation.

Building effects were identified as the main hazard for this type of side-by-side calibration design. To assess the building influence on the analysis, the population sample was examined. Reviewing the spatial distribution of data, some tapering off of resources were observed as the sensor placement neared the north and south buildings. However, these smaller resources still exceeded 1200 data points and, therefore, the building effect was not identified as a major concern at this point in the analysis.

Later, once the relative calibration results were being assimilated, the interpretation changed. The anomalous character of the results in the northern most sonic, position 1, and some of the position 2 results implied that the local building effects had exceeded the ability of the design/method to discern a clear calibration difference. Two suggestions were given for improving this situation in future relative calibration efforts. One was to design the north side of the lateral array no closer to the north building than position 3 (about 7.4 m from the wall). The south side of the array didn't show as many unusual results; therefore, keeping or pruning this position from the lateral array was left optional. Taking a conservative approach, position 10 would also be eliminated. Thus, the revised conservative calibration group would be limited

to only seven sonics at one time. A second approach suggested was to accept only velocities greater than 10 m/s. This suggestion may not be practical, outside of the typical NM "windy season."

Another recommendation expanded on the alternate threshold concept. Namely, when defining the relative calibration criteria for qualified data, increase the 1 m/s minimum velocity threshold. One post-analysis exercise reviewed a 5 m/s threshold and saw that the standard sonic provided 997 samples for comparison with other sonics. This amount was about a 65–75% drop in qualified data and there was no guarantee that the "uncalibrated" sonics would overlap those qualified data points provided by the standard. Taking this 5 m/s threshold concept one step further, a worse-case trial exercise was run for an uncalibrated sonic in position 1. Only 543 samples were listed as qualified. Correlating these samples with those of the standard was not pursued, but the use of a higher threshold was acknowledged as a possible improvement worth consideration.

The relative calibration results were analyzed by examining each of the Pre- and Post-*W07US* Calibration groups separately, as a function of the u-, v-, and w- wind components. The northern two positions in the lateral array were flagged as incongruous with the other results. The v-component in the Post-*W07US* Calibration dataset was also flagged as having three data points inconsistent with the other findings. Ignoring these concerns for reasons cited earlier, similar trends were observed in the remaining Pre- and Post-*W07US* Calibration Δu, Δv, and Δw results. All remaining calibration differences were within ±0.5 m/s; and the Pre-*W07US* Calibration Groups fell within ±0.3 m/s.

Each Δ component held a unique general pattern: Δu showed an underestimation of the standard that gradually decreased from positions 3 to 4 and increased from positions 6 through 10. Δv showed a negative slope line from positions 3 through 10. What started as an overestimation of the standard on the north side of the array ended up as an underestimation on the south side. The Δw trend showed a positive slope. The underestimation of the standard on the north side shifted to an overestimation on the south side. While some of these trends may be linked to the building proximity, the data did hover around the ideal result of zero. This near zero observation was the anticipated outcome of the calibration effort.

There were several lessons learned, which we summarize here:

1. To avoid the building's influence, sensors should be mounted no closer to the north building than position 3 (about 7.4 m from the wall) and no closer to the south building than position 10 (about 9 m from the wall). The conservative recommendation was to place the southern most sonic in position 9.

2. The calibration results may be more closely aligned to a wind tunnel if the thresholds for acceptable sensor differences were increased to from 1 m/s to 5 m/s, or even 12 m/s. Note: Data from the natural environment may not be available.

3. The NIST standard sonics were mounted at the lateral array end points. This choice helped anchor the interpretation of the calibration data analysis.

4. Position 5 in the 10-position lateral array was the best location between the test site buildings for the standard sonic. This position remained consistent for all Pre- and Post-*W07US* calibration group data acquisition periods.

5. The sensor mounting specifications (sensor height above ground and distance between sensors) showed no hint of interference for the westerly and easterly airflows. Therefore, the 2.5 m AGL and 1–2 m separation between sensors are recommended for future side-by-side calibration exercises.

In conclusion, we have observed that the component data acquired by these sensors are within 0.5 m/s of the standard sensor, with some additional sensors being much more closely aligned with the standard. This result may not be as tightly aligned as the controlled environment of a NIST wind tunnel calibration; however, since this exercise used only the natural airflow as the medium for the side-by-side comparisons, these results were considered acceptable.

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Appendix A. Side-By-Side Sonic Calibration References

The *W07US* side-by-side calibration was conducted before and after the *W07US* field study execution. The tables within this appendix document the Pre- and Post-*W07US* calibration groups, data acquisition dates, sonic position number in the 10-mount lateral array, sonic serial number, vertical sonic height (AGL), horizontal distance between sensors and the ground conditions under each mounted sonic. The following are some general notes regarding the content of the tables:

- The open volume of air through which the sonic sampled wind data was relatively large. Therefore, the height measurements in the table were taken from the ground to the top of the black electronic box on the sonic. From this point, a standard 0.32 m can be added to the height value in order to establish the sensor's height. In general, the sensor height was about 2.5 m AGL.
- The ground conditions under each mounted-sonic were either gravel or pavement.
- Since ambient measurements were somewhat subjective, the initials of the professional taking measurements were included in the table.

A-1 Pre-*W07US* Calibration

The Pre-*W07US* calibration data acquisition periods were a function of the available wind conditions and were therefore variable in length. During Group II, an unexpected USB failure occurred and therefore the sonics affected were included in the first part of Group III. For accounting purposes, Group III was labeled, III-A and III-B. The dates for the duration are self-explanatory. Note that the sonic in position 9 (#1370) sampled data during all of Groups II and III.

The last Pre-*W07US* calibration table, labeled "Group III-B, 2007 Mar 05, Group III-End", includes the measurements of all sonics just prior to the use in the *W07US* field execution.

Six sonics were calibrated against a NIST standard just prior to the *W07US*. These were noted in the "Calibrated Sonics" table. The other two sonics in this table were calibrated standards in *W05US* and *W07US*.

Table A-1. Pre-*W07US* sonic calibration configuration, Group I (2007 February 15–21) and Group II (2007 February 21–27).

	PRE-*W07US* Sonic Calibration Configuration 2007 Feb 15 - 2007 Mar 05						
	Building	Position Number	Sonic Serial Number	Height in Meters++ (AGL)	Distance between Sensors (Meters)	COMMENTS	
GROUP I: 2007 Feb 15-Feb 21	1622	0					Gravel
		1	**1330**	2.04	4.30	Bldg 1622 Wall to #1330 center=4.30m	Gravel
		2	1338	2.12	1.84	#1330 to #1338	Gravel
		3	1342	2.17	1.01	#1338 to #1342	Gravel
		4	1343	2.18	1.17	#1342 to #1343	Pavement
	STANDARD	**5**	**1341**	2.18	1.21	Standard: #1343 to #1341	Pavement
		6	1353	2.20	1.84	#1341 to #1353	Pavement
Measurements taken: 070215 by rb, gv		7	1354	2.23	1.19	#1353 to #1354	Pavement
		8	1355	2.25	1.14	#1354 to #1355	Gravel
		9	1356	2.24	1.17	#1355 to #1356	Gravel
		10	**1357**	2.26	1.78	#1356 to #1357	Gravel
	1621				9.00	#1357 to Bldg 1621 Wall	Gravel
Notes: 070215	++Height in Meters means:	Ground to top of black box on sonic; [For Ground to sensor center, add ~0.32m.] STANDARD's height from ground to sonic sensor center = 2.5m; to black box=2.18m Therefore, black box top to sonic sensor center is ~0.32m					

GROUP II: 2007 Feb 21-Feb 27	1622	0					Gravel
		1	**1360**	2.06	4.30	Bldg 1622 Wall to #1360 center =4.30m	Gravel
		2	1358	2.12	1.84	#1360 to #1358	Gravel
		3	1359	2.18	1.01	#1358 to #1359	Gravel
		4	1361	2.19	1.17	#1359 to #1361	Pavement
	STANDARD	**5**	**1341**	2.17	1.20	Standard: #1361 to #1341	Pavement
		6	1362	2.20	1.84	#1341 to #1362	Pavement
		7	1368	2.23	1.20	#1362 to #1368	Pavement
Measurements taken: 070221 by rb, mb, gv		8	1369	2.26	1.14	#1368 to #1369	Gravel
		9	1370	2.25	1.17	#1369 to #1370	Gravel
		10	**1374**	2.27	1.78	#1370 to #1374	Gravel
	1621				9.00	#1374 to Bldg 1621 Wall	Gravel
Notes:	++Height in Meters means:	Ground to top of black box on sonic; [For Ground to sensor center, add ~0.32m.] STANDARD's height from ground to sonic sensor center = 2.5m; to black box=2.18m Therefore, black box top to sonic sensor center is ~0.32m					

Table A-2. Pre-*W07US* sonic calibration configuration, Group III-A (2007 February 27–Mar 2) and Group III-B (2007 March 2–5).

	PRE-*W07US* Sonic Calibration Configuration 2007 Feb 15 - 2007 Mar 05						
	Building	**Position Number**	**Sonic Serial Number**	**Height in Meters++ (AGL)**	**Distance between Sensors (Meters)**	**COMMENTS**	
GROUP III-A:	1622	0					Gravel
2007 Feb 27-		1	**0637**	2.04	4.30	Bldg 1622 Wall to #0637 center =4.30m	Gravel
Mar 02		2	1371	2.11	1.84	#0637 to #1371	Gravel
		3	1372	2.19	1.01	#1371 to #1372	Gravel
		4	1373	2.19	1.17	#1372 to #1373	Pavement
	STANDARD	**5**	**1341**	2.17	1.20	Standard: #1373 to #1341	Pavement
		6	1375	2.21	1.84	#1341 to #1375	Pavement
		7	1368	2.23	1.20	#1375 to #1368	Pavement
Measurements		8	1369	2.27	1.14	#1368 to #1369	Gravel
taken: 070227		9	1370	2.25	1.17	#1369 to #1370	Gravel
by rb, sd, gv		10	**1374**	2.27	1.78	#1370 to #1374	Gravel
	1621				9.00	#1374 to Bldg 1621 Wall	Gravel
Notes:	++Height in Meters means:		Ground to top of black box on sonic; [For Ground to sensor center, add ~0.32m.] STANDARD's height from ground to sonic sensor center = 2.5m; to black box=2.18m Therefore, black box top to sonic sensor center is ~0.32m				

GROUP III-B:	1622	0					Gravel
2007 Mar 02-		1	**0637**	2.04	4.30	Bldg 1622 Wall to #0637 center =4.30m	Gravel
Mar 05		2	1371	2.11	1.83	#0637 to #1371	Gravel
		3	1372	2.18	1.01	#1371 to #1372	Gravel
		4	1373	2.18	1.17	#1372 to #1373	Pavement
	STANDARD	**5**	**1341**	2.21	1.25	Standard: #1373 to #1341	Pavement
		6	1375	2.20	1.84	#1341 to #1375	Pavement
		7	1376	2.23	1.15	#1375 to #1376	Pavement
Measurements		8	1377	2.26	1.14	#1376 to #1377	Gravel
taken: 070302		9	1370	2.25	1.18	#1377 to #1370	Gravel
by rb, mb, gv		10	**0638**	2.27	1.78	#1370 to #0638	Gravel
	1621				9.00	#0638 to Bldg 1621 Wall	Gravel
Notes:	++Height in Meters means:		Ground to top of black box on sonic; [For Ground to sensor center, add ~0.32m.] STANDARD's height from ground to sonic sensor center = 2.5m; to black box=2.18m Therefore, black box top to sonic sensor center is ~0.32m				

Table A-3. Pre-*W07US* sonic calibration configuration, Group III-END (2007 March 05) and Calibrated Sonics.

	PRE-*W07US* Sonic Calibration Configuration 2007 Feb 15 - 2007 Mar 05						
	Building	Position Number	Sonic Serial Number	Height in Meters++ (AGL)	Distance between Sensors (Meters)	COMMENTS	
GROUP III-B:	1622	0					Gravel
2007 Mar 05		1	**0637**	2.04	4.30	Bldg 1622 Wall to #0637 center =4.30m	Gravel
(Group III-End)		2	1371	2.11	1.84	#0637 to #1371	Gravel
		3	1372	2.19	1.01	#1371 to #1372	Gravel
		4	1373	2.18	1.17	#1372 to #1373	Pavement
	STANDARD	5	**1341**	2.21	1.25	Standard: #1373 to #1341	Pavement
		6	1375	2.20	1.84	#1341 to #1375	Pavement
		7	1376	2.23	1.15	#1375 to #1376	Pavement
Measurements		8	1377	2.26	1.14	#1376 to #1377	Gravel
taken: 070305		9	1370	2.25	1.18	#1377 to #1370	Gravel
by rb, mb		10	**0638**	2.27	1.78	#1370 to #0638	Gravel
	1621				9.00	#0638 to Bldg 1621 Wall	Gravel
Notes:	++Height in Meters means:		Ground to top of black box on sonic; [For Ground to sensor center, add ~0.32m] STANDARD's height from ground to sonic sensor center = 2.5m; to black box=2.18m Therefore, black box top to sonic sensor center is ~0.32m				

	Calibrated Sonics	
1341	Group I,II,III	2007 Standard-Calibrated
1330	Group I	2005 Standard
1357	Group I	Repaired-Calibrated
1360	Group II	Repaired-Calibrated
1374	Group II	Repaired-Calibrated
637	Group III-A	Repaired-Calibrated
638	Group III-A	Repaired-Calibrated
637	Group III-B	Repaired-Calibrated
638	Group III-B	Repaired-Calibrated

A-2 Post-*W07US* Calibration

The Post-*W07US* calibration data acquisition periods were a function of the available wind conditions and were, therefore, variable in length. No data acquisition interruptions occurred; therefore, the three groups were executed sequentially.

One of the lessons learned from the Pre-*W07US* calibration exercise was that sensors mounted in a public access area have a greater potential for being moved than in a rural area. Thus, the vertical and horizontal sonic positions were taken before and after each group acquired data, and are labeled "-START-" and "-END-", respectively.

Six sonics were calibrated against a NIST standard just prior to the *W07US*. These were noted in the final table, labeled "Calibrated Sonics." The other two sonics in this table were calibrated standards in *W05US* and *W07US*.

Table A-4. Post-*W07US* sonic calibration configuration, Group I (2007 April 9–11).

	POST-*W07US* Sonic Calibration Configuration 2007 Apr 9 - 19						
	Building	**Position Number**	**Sonic Serial Number**	**Height in Meters++ (AGL)**	**Distance between Sensors (Meters)**	**COMMENTS**	
GROUP I:	1622	0					Gravel
- START -		1	**1330**	2.15	4.55	Bldg 1622 Wall to #1330 center=4.55m	Gravel
		2	1338	2.20	1.80	#1330 to #1338	Gravel
2007		3	1342	2.20	1.04	#1338 to #1342	Gravel
April 9 - 11		4	1343	2.20	1.15	#1342 to #1343	Pavement
	STANDARD	**5**	**1341**	2.17	0.98	Standard: #1343 to #1341	Pavement
		6	1353	2.25	1.82	#1341 to #1353	Pavement
Measurements		7	1354	2.23	1.07	#1353 to #1354	Pavement
taken: 070409		8	1355	2.30	1.15	#1354 to #1355	Gravel
by mb, hf		9	1356	2.27	1.04	#1355 to #1356	Gravel
		10	**1357**	2.23	1.87	#1356 to #1357	Gravel
	1621				9.20	#1357 to Bldg 1621 Wall	Gravel
Notes: 070215	++Height in Meters means:		Ground to top of black box on sonic; [For Ground to sensor center, add ~0.32m.] STANDARD's height from ground to sonic sensor center = 2.5m; to black box=2.18m Therefore, black box top to sonic sensor center is ~0.32m				

GROUP I:	1622	0					Gravel
- END -		1	**1330**	2.13	4.55	Bldg 1622 Wall to #1330 center=4.55m	Gravel
		2	1338	2.16	1.80	#1330 to #1338	Gravel
2007		3	1342	2.21	1.05	#1338 to #1342	Gravel
April 9 - 11		4	1343	2.17	1.16	#1342 to #1343	Pavement
	STANDARD	**5**	**1341**	2.17	0.98	Standard: #1343 to #1341	Pavement
		6	1353	2.20	1.82	#1341 to #1353	Pavement
Measurements		7	1354	2.22	1.07	#1353 to #1354	Pavement
taken: 070411		8	1355	2.26	1.15	#1354 to #1355	Gravel
by mb, gv		9	1356	2.26	1.04	#1355 to #1356	Gravel
		10	**1357**	2.21	1.87	#1356 to #1357	Gravel
	1621				9.16	#1357 to Bldg 1621 Wall	Gravel
Notes:	++Height in Meters means:		Ground to top of black box on sonic; [For Ground to sensor center, add ~0.32m.] STANDARD's height from ground to sonic sensor center = 2.5m; to black box=2.18m Therefore, black box top to sonic sensor center is ~0.32m				

Table A-5. Post-*W07US* sonic calibration configuration, Group II (2007 April 11–13).

	POST-*W07US* Sonic Calibration Configuration 2007 Apr 9 - 19						
	Building	**Position Number**	**Sonic Serial Number**	**Height in Meters++ (AGL)**	**Distance between Sensors* (Meters)**	**COMMENTS***	
GROUP II:	1622	0					Gravel
- START -		1	**1360**	2.12	4.55	Bldg 1622 Wall to #1360 center =4.55m	Gravel
		2	1358	2.17	1.79	#1360 to #1358	Gravel
2007		3	1359	2.21	1.04	#1358 to #1359	Gravel
April 11 - 13		4	1361	2.18	1.16	#1359 to #1361	Pavement
	STANDARD	**5**	**1341**	2.18	0.99	Standard: #1361 to #1341	Pavement
		6	1362	2.21	1.82	#1341 to #1362	Pavement
		7	1368	2.23	1.07	#1362 to #1368	Pavement
Measurements		8	1369	2.26	1.15	#1368 to #1369	Gravel
taken: 070411		9	1370	2.27	1.04	#1369 to #1370	Gravel
by mb, rb,gv,sd		10	**1374**	2.22	1.87	#1370 to #1374	Gravel
	1621				9.18	#1374 to Bldg 1621 Wall	Gravel
Notes:	++Height in Meters means:	Ground to top of black box on sonic; [For Ground to sensor center, add ~0.32m.] STANDARD's height from ground to sonic sensor center = 2.5m; to black box=2.18m Therefore, black box top to sonic sensor center is ~0.32m					

GROUP II:	1622	0					Gravel
- END -		1	**1360**	2.12	4.55	Bldg 1622 Wall to #1360 center =4.55m	Gravel
		2	1358	2.17	1.80	#1360 to #1358	Gravel
2007		3	1359	2.20	1.04	#1358 to #1359	Gravel
April 11 - 13		4	1361	2.17	1.16	#1359 to #1361	Pavement
	STANDARD	**5**	**1341**	2.18	0.99	Standard: #1361 to #1341	Pavement
		6	1362	2.21	1.83	#1341 to #1362	Pavement
		7	1368	2.23	1.08	#1362 to #1368	Pavement
Measurements		8	1369	2.26	1.15	#1368 to #1369	Gravel
taken: 070413		9	1370	2.26	1.04	#1369 to #1370	Gravel
by rb, hf		10	**1374**	2.22	1.87	#1370 to #1374	Gravel
	1621				9.16	#1374 to Bldg 1621 Wall	Gravel
Notes:	++Height in Meters means:	Ground to top of black box on sonic; [For Ground to sensor center, add ~0.32m.] STANDARD's height from ground to sonic sensor center = 2.5m; to black box=2.18m Therefore, black box top to sonic sensor center is ~0.32m					

Table A-6. Post-*W07US* sonic calibration configuration, Group III (2007 April 13–19) and Calibrated Sonics.

	POST-*W07US* Sonic Calibration Configuration 2007 Apr 9 - 19						
	Building	Position Number	Sonic Serial Number	Height in Meters++ (AGL)	Distance between Sensors* (Meters)	COMMENTS*	
GROUP III:	1622	0					Gravel
- START -		1	**0637**	2.13	4.55	Bldg 1622 Wall to #0637 center =4.55m	Gravel
		2	1371	2.17	1.80	#0637 to #1371	Gravel
2007		3	1372	2.20	1.04	#1371 to #1372	Gravel
April 13 - 19		4	1373	2.17	1.16	#1372 to #1373	Pavement
	STANDARD	**5**	**1341**	2.18	0.99	Standard: #1373 to #1341	Pavement
		6	1375	2.21	1.82	#1341 to #1375	Pavement
		7	1376	2.23	1.08	#1375 to #1376	Pavement
Measurements		8	1377	2.26	1.15	#1376 to #1377	Gravel
taken: 070413		9	1370	2.26	1.04	#1377 to #1370	Gravel
by rb, hf		10	**0638**	2.21	1.87	#1370 to #0638	Gravel
	1621				9.17	#0638 to Bldg 1621 Wall	Gravel
Notes:	++Height in Meters means:	Ground to top of black box on sonic; [For Ground to sensor center, add ~0.32m.] STANDARD's height from ground to sonic sensor center = 2.5m; to black box=2.18m Therefore, black box top to sonic sensor center is ~0.32m					

GROUP III:	1622	0					Gravel
- END -		1	**0637**	2.13	4.55	Bldg 1622 Wall to #0637 center =4.55m	Gravel
		2	1371	2.17	1.80	#0637 to #1371	Gravel
2007		3	1372	2.20	1.04	#1371 to #1372	Gravel
April 13 - 19		4	1373	2.18	1.16	#1372 to #1373	Pavement
	STANDARD	**5**	**1341**	2.18	0.99	Standard: #1373 to #1341	Pavement
		6	1375	2.21	1.82	#1341 to #1375	Pavement
		7	1376	2.23	1.08	#1375 to #1376	Pavement
Measurements		8	1377	2.26	1.16	#1376 to #1377	Gravel
taken: 070419		9	1370	2.26	1.05	#1377 to #1370	Gravel
by rb, hf, gv		10	**0638**	2.22	1.87	#1370 to #0638	Gravel
	1621				9.17	#0638 to Bldg 1621 Wall	Gravel
Notes:	++Height in Meters means:	Ground to top of black box on sonic; [For Ground to sensor center, add ~0.32m.] STANDARD's height from ground to sonic sensor center = 2.5m; to black box=2.18m Therefore, black box top to sonic sensor center is ~0.32m					

	Calibrated Sonics	
1341	Group I,II,III	2007 Standard-Calibrated
1330	Group I	2005 Standard
1357	Group I	Repaired-Calibrated
1360	Group II	Repaired-Calibrated
1374	Group II	Repaired-Calibrated
637	Group III	Repaired-Calibrated
638	Group III	Repaired-Calibrated

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Appendix B. Numerically Ordered Sonics and their Pre- and Post-*W07US* Calibration Positions

Table B-1. A numerically ordered list of the sonics and their calibration lateral array position assignments.

PRE-Calibration Group Number	PRE-Calibration Dates 2007
1	**Feb 15-21**
2	**Feb 21-27**
3a	**Feb 27-Mar 2**
3b	**Feb Mar 2-5**
3	**Feb 27-Mar 5**
2, 3	**Feb 21-Mar 5**

POST-Calibration Group Number	POST-Calibration Dates 2007
1	**Apr 9-11**
2	**Apr 11-13**
3	**Apr 13-19**
2, 3	**Apr 11-19**

	Sonic Serial Number	PRE-Calibration Group Number	PRE-Calibration Position Number
1	**0637**	3	1
2	**0638**	3b	10
3	**1330**	1	1
4	1338	1	2
5	**1341-STANDARD**	**1, 2, 3**	**5**
6	1342	1	3
7	1343	1	4
8	1353	1	6
9	1354	1	7
10	1355	1	8
11	1356	1	9
12	**1357**	1	10
13	1358	2	2
14	1359	2	3
15	**1360**	2	1
16	1361	2	4
17	1362	2	6
18	1368	2, 3a	7
19	1369	2, 3a	8
20	1370	2, 3	9
21	1371	3	2
22	1372	3	3
23	1373	3	4
24	**1374**	2, 3a	10
25	1375	3	6
26	1376	3b	7
27	1377	3b	8

Sonic Serial Number	POST-Calibration Group Number	POST-Calibration Position Number
0637	3	1
0638	3	10
1330	1	1
1338	1	2
1341-STANDARD	1	**5**
1342	1	3
1343	1	4
1353	1	6
1354	1	7
1355	1	8
1356	1	9
1357	1	10
1358	2	2
1359	2	3
1360	2	1
1361	2	4
1362	2	6
1368	2	7
1369	2	8
1370	2, 3	9
1371	3	2
1372	3	3
1373	3	4
1374	2	10
1375	3	6
1376	3	7
1377	3	8

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Appendix C. Three-dimensional View of the Pre- and Post-*W07US* Calibration Cumulative Qualified 1-min Averages.

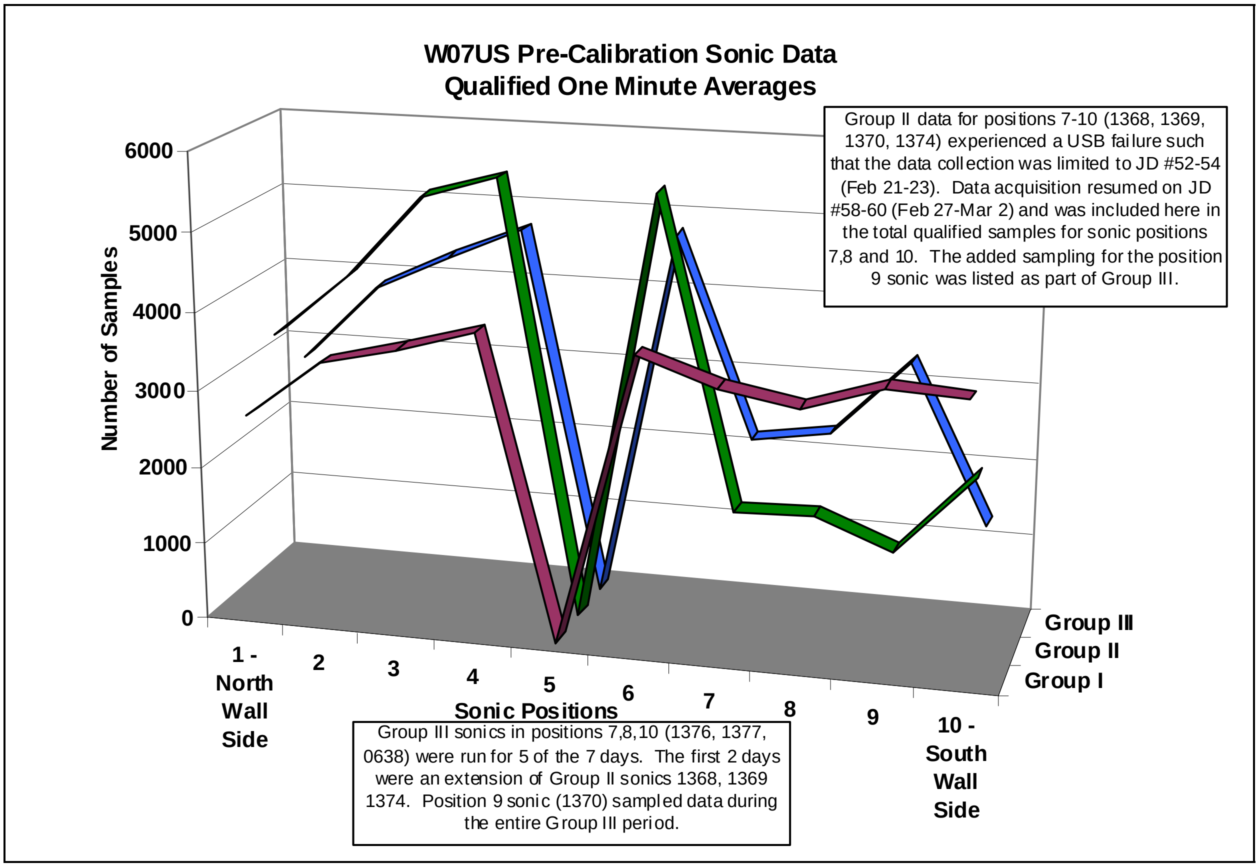

Figure C-1. A three-dimensional chart showing by group, the cumulative percentage of qualified 1-min averages for the Pre-Calibration dataset.

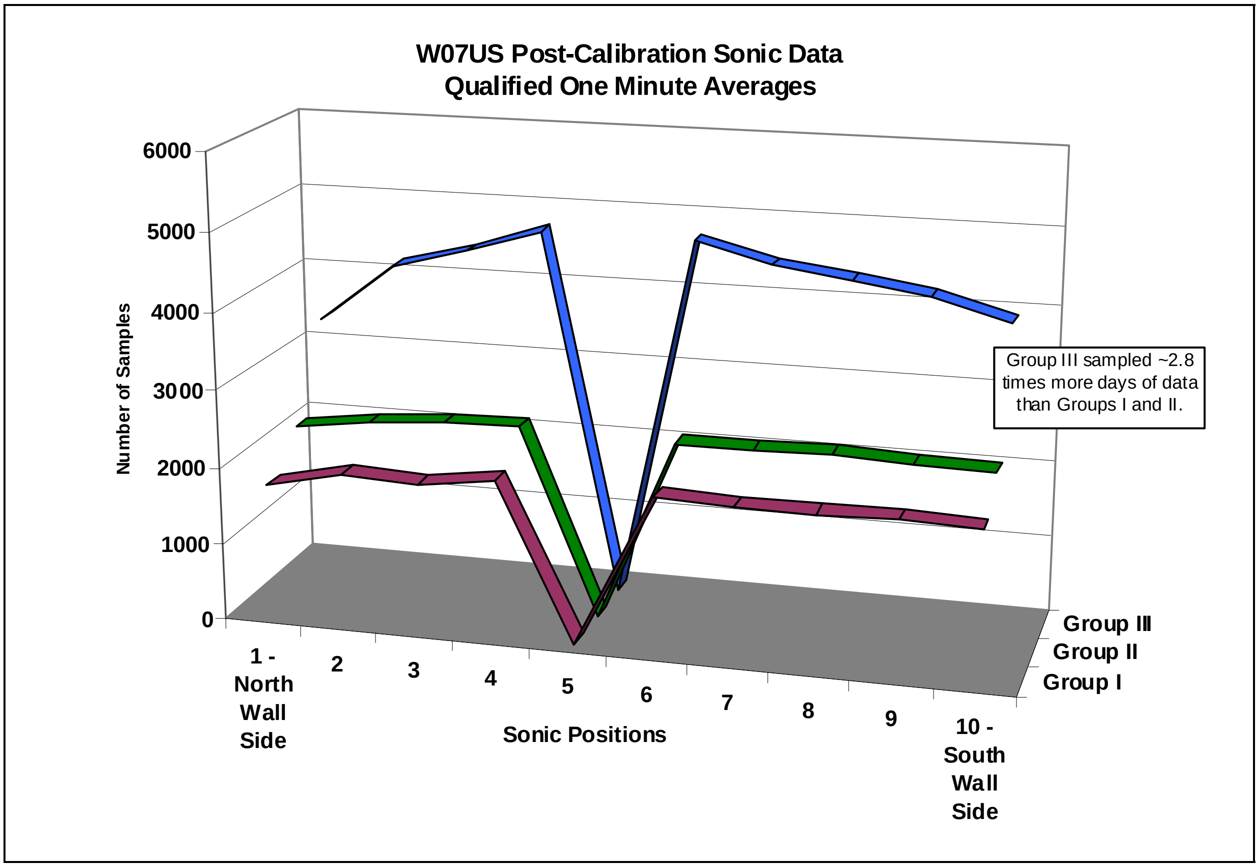

Figure C-2. A three-dimensional chart showing by group, the cumulative percentage of qualified 1-min averages for the Post-Calibration dataset.

Note: Section 3.3.4 explains why Group III sampled more days of data than Groups I and II.

Appendix D. Average Relative Calibration Wind Direction Results

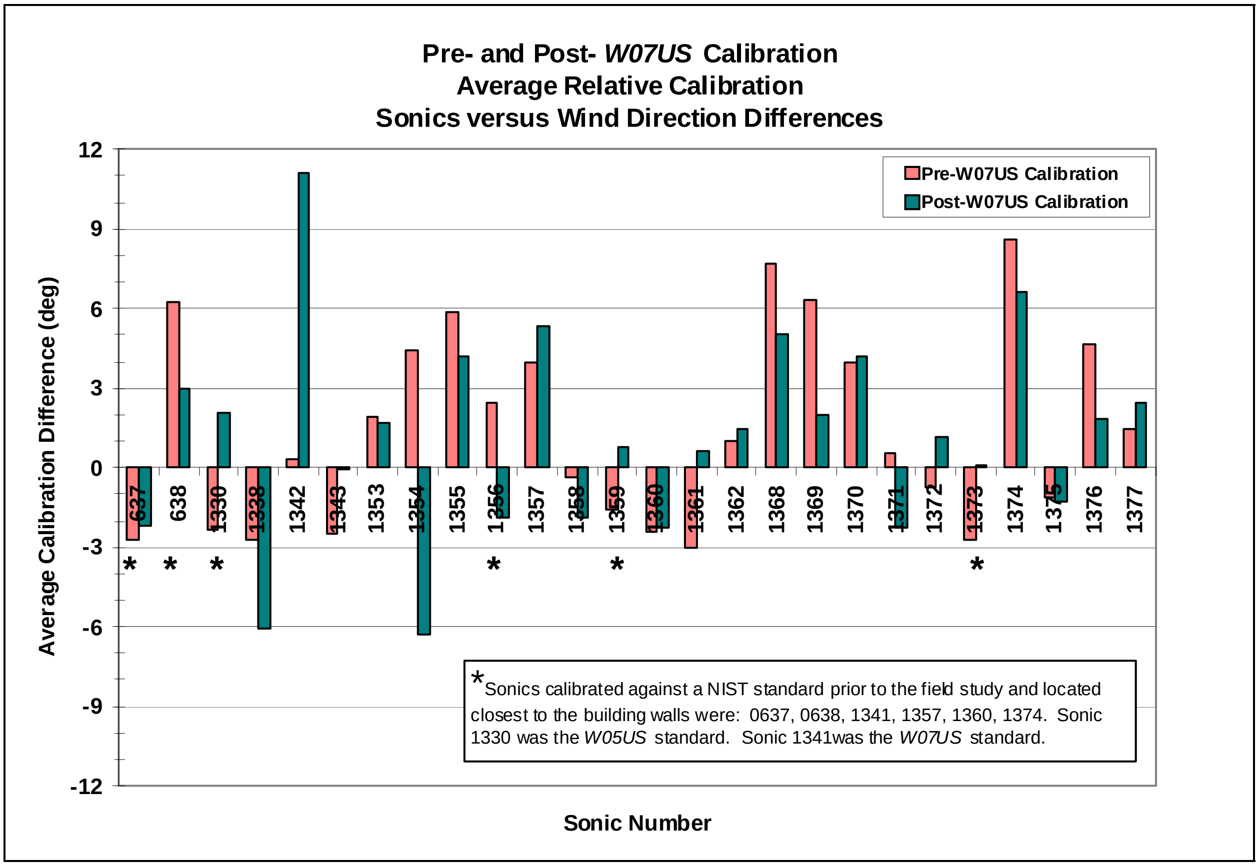

Figure D-1. A graphical representation of the relative calibration results for wind direction.

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Appendix E. Numerical Pre- and Post-*W07US* Relative Calibration Results

Table E-1. Pre-*W07US* relative calibration results.

WSMR 2007 Urban Study Pre-Calibration Data 1 Min Avg Deltas = Sensor - Standard												
Sonic Number	Group Number	Number of samples	Wind Speed (m/s)	Standard Deviation (m/s)	Wind Direction (deg)	Standard Deviation (m/s)	u-component (m/s)	Standard Deviation (m/s)	v-component (m/s)	Standard Deviation (m/s)	w-component (m/s)	Standard Deviation (m/s)
1341	1, 2, 3											
637	3	2855	-1.10	1.70	-2.71	7.86	-0.99	1.65	0.41	0.64	-0.15	0.38
638	3*	1311	-0.13	0.55	6.22	6.65	-0.15	0.56	-0.17	0.47	0.07	0.41
1330	1	2618	-0.90	1.64	-2.32	6.57	-0.77	1.60	0.30	0.61	-0.16	0.38
1338	1	3381	-0.28	0.85	-2.74	4.41	-0.23	0.78	0.20	0.40	-0.16	0.28
1342	1	3613	-0.14	0.51	0.32	3.25	-0.12	0.48	0.03	0.25	-0.06	0.19
1343	1	3901	-0.03	0.23	-2.49	1.87	-0.01	0.21	0.10	0.18	-0.05	0.12
1353	1	3753	0.02	0.24	1.92	2.44	-0.01	0.21	-0.11	0.17	0.14	0.22
1354	1	3420	-0.03	0.51	4.44	4.50	-0.06	0.51	-0.20	0.39	0.18	0.29
1355	1	3252	-0.07	0.58	5.89	5.17	-0.12	0.57	-0.27	0.48	0.23	0.38
1356	1	3569	-0.05	0.64	2.44	5.70	-0.05	0.63	-0.09	0.39	0.23	0.41
1357	1	3501	-0.14	0.75	3.93	6.87	-0.06	0.76	-0.19	0.49	0.20	0.47
1358	2	4245	-0.56	1.10	-0.39	4.97	-0.52	1.02	0.15	0.59	-0.19	0.38
1359	2	5310	-0.17	0.71	-1.59	3.21	-0.13	0.65	0.20	0.32	-0.07	0.25
1360	2	3404	-1.43	1.98	-2.45	7.06	-1.33	1.91	0.44	0.80	-0.18	0.51
1361	2	5599	-0.02	0.34	-3.04	1.74	0.01	0.29	0.28	0.24	-0.13	0.18
1362	2	5523	0.08	0.34	1.00	2.11	0.06	0.30	-0.12	0.19	0.21	0.24
1368	2*, 3*	1543	-0.07	0.53	7.70	4.20	-0.12	0.53	-0.45	0.54	0.13	0.27
1369	2*, 3*	1592	-0.10	0.58	6.29	4.74	-0.13	0.57	-0.36	0.50	0.22	0.37
1370	2*, 3	4547	-0.05	0.89	3.98	6.30	-0.08	0.88	-0.21	0.48	0.26	0.41
1371	3	3842	-0.44	0.99	0.58	5.66	-0.38	0.93	0.13	0.48	-0.16	0.30
1372	3	4316	-0.26	0.65	-0.76	4.32	-0.21	0.59	0.15	0.32	-0.09	0.21
1373	3	4732	-0.09	0.31	-2.74	2.40	-0.05	0.27	0.17	0.19	-0.07	0.14
1374	2*, 3*	2255	-0.26	1.23	8.57	7.94	-0.29	1.23	-0.58	0.73	0.21	0.48
1375	3	4784	0.13	0.36	-1.11	2.66	0.12	0.34	0.00	0.22	0.08	0.17
1376	3*	2186	0.00	0.28	4.65	4.38	-0.04	0.27	-0.14	0.26	0.09	0.19
1377	3*	2341	0.03	0.34	1.50	4.96	0.01	0.32	-0.07	0.22	0.13	0.24
	Average:	3515	-0.23	0.72	1.43	4.69	-0.22	0.69	-0.02	0.41	0.03	0.30
	Std Dev:	1196	0.38	0.47	3.65	1.85	0.34	0.46	0.26	0.18	0.16	0.11
	Max:	5599	0.13	1.98	8.57	7.94	0.12	1.91	0.44	0.80	0.26	0.51
	Min:	1311	-1.43	0.23	-3.04	1.74	-1.33	0.21	-0.58	0.17	-0.19	0.12

* = sonic was run for part of Group only.

Note: Taken from the *Diff_Stats_Xcel_Pre1Min_070824* file.

Table E-2. Post-*W07US* relative calibration results.

WSMR 2007 Urban Study Post-Calibration Data 1 Min Avg Deltas = Sensor - Standard												
Sonic Number	Group Number	Number of samples	Wind Speed (m/s)	Standard Deviation (m/s)	Wind Direction (deg)	Standard Deviation (m/s)	u-component (m/s)	Standard Deviation (m/s)	v-component (m/s)	Standard Deviation (m/s)	w-component (m/s)	Standard Deviation (m/s)
1341	1, 2, 3											
637	3	3379	-0.90	1.58	-2.18	6.64	-0.89	1.51	0.28	0.54	-0.22	0.42
638	3	3934	-0.16	0.86	2.98	7.67	0.02	0.81	-0.28	0.51	0.10	0.47
1330	1	1727	-2.46	2.06	2.03	6.16	-2.37	2.06	0.22	0.90	-0.32	0.59
1338	1	1941	-0.71	1.17	-6.09	3.50	-0.65	1.07	0.86	0.46	-0.43	0.45
1342	1	1903	-0.25	0.66	11.15	2.17	-0.49	0.71	-1.18	0.89	-0.42	0.34
1343	1	2035	-0.02	0.29	-0.07	1.08	-0.02	0.27	0.03	0.13	-0.25	0.20
1353	1	2002	0.09	0.34	1.72	1.70	0.05	0.30	-0.25	0.20	0.17	0.23
1354	1	1963	0.04	0.49	-6.27	2.08	0.08	0.53	0.75	0.50	0.32	0.33
1355	1	1950	0.01	0.55	4.21	2.41	-0.08	0.49	-0.53	0.38	0.33	0.45
1356	1	1976	0.06	0.64	-1.86	3.01	0.07	0.62	0.22	0.41	0.46	0.51
1357	1	1932	-0.07	0.72	5.32	3.45	-0.16	0.67	-0.64	0.52	0.35	0.65
1358	2	2329	-1.22	1.49	-1.87	5.67	-1.26	1.48	0.36	0.54	-0.28	0.37
1359	2	2411	-0.08	0.62	0.81	2.56	-0.09	0.59	-0.02	0.29	-0.31	0.31
1360	2	2188	-1.19	1.81	-2.27	5.84	-1.17	1.75	0.35	0.59	-0.40	0.54
1361	2	2433	0.03	0.26	0.59	1.24	0.02	0.25	-0.04	0.13	-0.23	0.20
1362	2	2365	0.09	0.38	1.45	2.24	0.08	0.35	-0.17	0.21	0.04	0.22
1368	2	2362	-0.04	0.43	5.00	2.58	-0.08	0.38	-0.49	0.30	0.02	0.30
1369	2	2390	-0.09	0.57	1.96	3.65	-0.09	0.52	-0.18	0.33	0.23	0.44
1370	2, 3	6539	-0.09	0.65	4.19	5.50	-0.03	0.59	-0.35	0.43	0.18	0.44
1371	3	4145	-0.26	0.85	-2.27	4.77	-0.30	0.78	0.19	0.38	-0.21	0.35
1372	3	4394	-0.12	0.53	1.19	3.46	-0.15	0.49	0.01	0.29	-0.20	0.31
1373	3	4705	0.00	0.24	0.12	1.87	-0.03	0.22	0.01	0.12	-0.11	0.16
1374	2	2318	-0.28	0.76	6.65	6.73	-0.31	0.72	-0.59	0.52	0.15	0.59
1375	3	4713	0.06	0.35	-1.27	3.03	0.10	0.31	-0.01	0.22	-0.03	0.18
1376	3	4466	-0.03	0.45	1.87	3.98	0.04	0.40	-0.15	0.26	0.12	0.27
1377	3	4335	-0.04	0.56	2.46	5.22	0.04	0.50	-0.22	0.34	0.16	0.36
	Average:	2955	-0.29	0.74	1.14	3.78	-0.29	0.71	-0.07	0.40	-0.03	0.37
	Std Dev:	1268	0.58	0.49	3.78	1.87	0.57	0.48	0.43	0.20	0.27	0.14
	Max:	6539	0.09	2.06	11.15	7.67	0.10	2.06	0.86	0.90	0.46	0.65
	Min:	1727	-2.46	0.24	-6.27	1.08	-2.37	0.22	-1.18	0.12	-0.43	0.16

Note: Taken from the *Diff_Stats_Xcel_Post1Min_070907* file.

Acronyms

AGL	above ground level
ARL	U.S. Army Research Laboratory
ASTM	American Society of Testing and Materials
c	speed of sound
DAS	data acquisition system
dec hr	decimal hours
GB	gigabytes
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NTP	Network Time Protocol
rpm	rotations per minute
SOS	speed of sound
Temp	temperature
U	u-component
USB	Universal Serial Bus
V	v-component
W	w-component
W03US	*WSMR 2003 Urban Study*
W05US	*WSMR 2005 Urban Study*
W07US	*WSMR 2007 Urban Study*
WD	wind direction
WS	wind speed
WSMR	White Sands Missile Range

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